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Parameter Analysis of Lunar Surface Navigation Utilizing Dilution-of-Precision Methodology With Lunar Orbiters

Bryan W. Welch
Glenn Research Center, Cleveland, Ohio

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Bryan W. Welch
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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Summary

With the NASA Vision for Space Exploration focusing on the return of astronauts to the Moon and eventually to Mars, architectures for new navigation concepts must be derived and analyzed. One such concept, developed by the Space Communications Architecture Working Group (SCAWG), is to place a constellation of satellites around the Moon. Previously completed analyses examined the performance of multiple satellite constellations and recommended a constellation oriented as a Walker polar 6/2/1 with a semimajor axis (SMA) of 9250 km. One requirement of the constellations that were examined was that they have continuous access to any location on the lunar surface. In this report, the polar 6/2/1 and polar 8/2/1, with equal semimajor axes, are examined in greater detail. The dilution-of-precision (DoP) methodology is utilized to examine the effects of longitude surface points, latitude surface points, elevation requirements, and modified failure modes for these two constellations with regard to system availability. Longitude study results show that points along a meridian closely approximate the results of a global set of data points. Latitude study results show that previous assumptions with regard to latitude spacing are adequate to simulate global system availability. Elevation study results show that global system availability curves follow a reverse sigmoid function. Modified failure mode study results show that the benefits of reorienting a failure mode constellation depend on the type of navigation system and the length of the integration period being used.

Introduction

In support of the NASA vision for Space Exploration for returning humans to the Moon (ref. 1), an extension of the position-fixing capability provided by the global positioning system (GPS) constellation (ref. 2) is being analyzed for use around the Moon. This extension would be provided through the introduction of a lunar network (LN) of spacecraft orbiting the Moon (refs. 3 and 4; (R. Nelson, Lunar Navigation System Alternatives for Continuous Full Surface Coverage, Space Communications Architecture Working Group (SCAWG), Aug. 18, 2005, to be published) and (R. Nelson, Navigation Options for Planetary Exploration, SCAWG, Feb. 9, 2006, to be published)). The present study extends previous analyses performed on several continuous lunar surface coverage constellations utilizing the generalized dilution-of-precision (DoP)-based navigation methodology for stationary lunar surface users (refs. 3, 5, 6; (R. Nelson, Lunar Navigation System Alternatives for Continuous Full Surface Coverage, SCAWG, Aug. 18, 2005, to be published) and (R. Nelson, Navigation Options for Planetary Exploration, SCAWG, Feb. 9, 2006, to be published)).

The two different constellations for the LN that are considered in the present study are a six- and an eight-satellite polar constellation (refs. 5 and 7). The two constellations have equal semimajor axes (SMA) set at 9250 km, and both utilize phasing between orbital planes. Since each constellation is a polar orbiting constellation, the inclination is defined as 90°. These two constellations were previously studied considering the possibility of the total failure of a single satellite (ref. 5), which reduced the six-satellite constellation to one with three satellites in one plane with 120° spacing and two satellites in one plane with 120° spacing (nonreflex angle) between the two satellites. The orbital planes were separated by 90° in the right ascension of the ascending node. Similarly, the eight-satellite constellation then contained one plane with four satellites at 90° spacing and a second plane with three satellites at 90° spacing (nonreflex angle) between the three satellites. Again, the orbital planes were separated by 90° in right ascension of the ascending node. Previously, there was no attempt to reconfigure the second orbital plane, which contained fewer satellites, such that the spacing between all the satellites in that plane was equal.

Various minimum user elevation angles were studied as there was not a set requirement for lunar surface users (ref. 5). Three elevation angles were studied: 5°, 10°, and 15°. Studies showed that an increase in the minimum elevation angle decreased system performance as a result of the decrease in the visibility of the satellites overhead. Two other parameters used in the previous study (ref. 5) were the spacing between the surface stationary locations. Longitudinal spacing was set at 15° and latitudinal spacing at 7.5° to create a grid of 554 distinct locations. Note that locations such as 90° N. 0° E. and 90° N. 45° E. are the same location and are not distinct. The previous study did not examine the effect of changing either the longitudinal or latitudinal spacing.

The present study will make extensions of the previous study utilizing the generalized DoP technique with the system availability metric for the various versions of DoP discussed on page 3 (GDoP, PDoP, HDoP) to attempt to answer the following questions:

1. How will the performance vary between the individual longitude points as compared with the mean performance of all the longitude points for each of the circles of latitude (since the performance of the system is time averaged over a lunar sidereal month)?
2. Was the 7.5° spacing between surface points too large to accurately model the system performance (since the performance of the system is spatially weighted)?
3. How does the elevation angle requirement fully affect system performance?
4. How do the modified failure mode constellations compare with the nonfailure mode and the failure mode nonmodified constellations?

Constellations

Two Kepler orbit propagated constellations are further examined: the polar 8/2/1 semimajor axis at 9250 km and the polar 6/2/1 SMA at 9250 km (refs. 5 and 7). Both constellations meet the requirement of providing continuous coverage by at least one satellite anywhere on the lunar surface at a minimum elevation angle of 10° for the surface user. The notation for the LN subsequently used, such as polar $N/p/f$ d km, is defined as the number of satellites, N; the number of orbital planes, p; the binary answer as to whether phasing exists in the mean anomaly between satellites in adjacent planes, f; and the SMA in kilometers, d. Table 1 lists the parameters of the two constellations considered herein.

The analysis in this report is also performed for a modified single failure mode of operation to determine loss of performance if there is a satellite outage. It is assumed that the outage is the worst case, in that the outage is permanent. The modified single failure mode assumes that the remaining satellites in the orbital plane that were affected by the outage have reoriented themselves to obtain equal spacing. Table 2 lists the parameters of the constellations in the modified failure mode.

Analysis

Generalized DoP

The analysis performed is a generalized version of the DoP metric (refs. 3 and 5), of which several forms are subsequently used. The generalized DoP is derived from the observability grammian, which is obtained by using the navigation user equations of motion and the associated sequence of measurements. The equations of motion and the measurement sequence are given in reference 5. It is shown that the DoP metric takes the following form, derived in reference 5:

$$\sqrt{\max\left\{\mathrm{eig}\left[\left(\sum_{t_0}^{t_n}\tilde{H}_0^T W \tilde{H}_0\right)^{-1}\right]\right\}} \qquad (1)$$

where

t_n	n^{th} time step since time step zero
t_0	time step zero
$\tilde{H}_0^T$	matrix transpose of $\tilde{H}_0$
$\tilde{H}_0$	state transitioned partial derivative measurement matrix
W	measurement weighting matrix

Variations of Generalized DoP

To relax the constraint of satellite coverage so as to invert the observability grammian, a number of augmentations to the lunar navigation system are considered in the analysis, as in previous analyses (ref. 5). These augmentations constrain the navigation solution and thereby reduce the number of required satellites in view. The augmentations include clock synchronization and good knowledge of the terrain, and they create four forms of DoP. The selected form of DoP used not only affects the required satellites in view but also affects the

TABLE 1.—LUNAR NETWORK CONSTELLATIONS

Constellation	Number of satellites	Number of planes	Semimajor axis (SMA), km	Inclination, deg	Eccentricity	Phasing number
Polar 8/2/1	8	2	9250	90	0	1
Polar 6/2/1	6	2	9250	90	0	1

TABLE 2.—MODIFIED FAILURE MODE LUNAR NETWORK CONSTELLATIONS

Constellation	Number of satellites	Number of planes	Semimajor axis (SMA), km	Inclination, deg	Eccentricity	Right ascension of ascending node (RAAN), deg
Polar 8/2/1	4	1	9250	90	0	0
	3	1	9250	90	0	90
Polar 6/2/1	3	1	9250	90	0	0
	2	1	9250	90	0	90

state transition and H-matrices used in the calculation. Also, note that throughout the analysis, both range and range-rate (Doppler) measurements are used to solve for position and time-bias (when appropriate) estimates only. No estimates were made for velocity or frequency bias, as the users are assumed to be stationary.

The first form of DoP, geometric dilution of precision (GDoP), is used in the GPS where the solution is obtained for the position of the user in three dimensions and for the time bias, resulting in the requirement of four navigation signals. Since two navigation signals are available from each satellite, only two satellites need be in view to kinematically solve for the user's position. Without two satellites in view, the solution will have to be integrated over time to be able to invert the solution and solve for the user's position and time bias. The GDoP metric is used to evaluate a navigation system operating in one-way mode without terrain information.

The second form of DoP, positional dilution of precision (PDoP), provides an estimate of user positioning accuracy for the case in which there is no time bias between orbiter clocks and user clocks, such as in a two-way mode of operation. PDoP results in the requirement of three navigation signals. Thus, the PDoP metric also requires two satellites in view to kinematically solve for the user's position. The PDoP metric is used to evaluate a navigation system operating in the two-way mode without terrain information.

The third form of DoP, horizontal/time dilution of precision (HTDoP), is applied when a user has knowledge of his altitude above the center of the Moon, but there is still a time bias from the source of the navigation signal. This situation also results in the requirement of three navigation signals, meaning that two satellites must be in view to kinematically solve for the user's topocentric north and east components along with the time bias. The HTDoP metric is used to evaluate a navigation system operating in one-way mode with terrain information.

Finally, the fourth form of DoP is the horizontal dilution of precision (HDoP). It provides an estimate of user positioning accuracy when both time and user altitude are known, only requiring two navigation signals, such as in the case of two-way mode of operation with good knowledge of terrain. This case requires that only one satellite be in view to kinematically solve for the user's topocentric north and east components. The HDoP metric is used to evaluate a navigation system operating in the two-way mode with terrain information.

System Availability

The underlying figure of merit (FOM) used for evaluating the performance associated with a navigation system is system availability (SA). System availability is defined herein as the proportion of time that the navigation system is predicted to provide performance at or below a specified level of DoP. In other words, the navigation system is defined as "available" when the appropriately chosen version of DoP falls below a certain threshold. For this study, as in the previous study, the threshold is set at 10. Furthermore, a DoP of 10, coupled with a 1-m user range error (URE) denotes a user state uncertainty of 10 m. Results provided are in terms of system availability for a given latency, whether the solution has zero latency (kinematic) or dynamic solutions of 15 min or 1 hr. Equation (2) describes how the system availability FOM is calculated, where n_{lat} is the number of latitude points in the simulation, n_{long} is the number of longitude points in the simulation, t_f is the number of time epochs in the simulation, and t_n is the total number of points in the simulation. The result is an estimate of the percentage of time that the system availability condition has been satisfied:

$$SA = 100 \times \frac{\sum_{m=1}^{t_n} \cos(lat_m) \times \sum_{n=1}^{t_f} (DoP_{n,m} <= \text{threshold})}{t_f \times n_{\mathrm{long}} \times \sum_{m=1}^{n_{\mathrm{lat}}} \cos(lat_m)} \tag{2}$$

Navigation Signal

The navigation signal requirements used in this study are given in table 3.

Longitude Study Simulation

The lunar surface was previously defined over a discrete set of 554 points on the surface (ref. 5). The longitude study analyzes the previous data as a whole and compares the performance of the individual longitude points along the various circles of latitude over the complete surface. Availability is computed from the limited set of data points and is compared with the previous SA results. The computations are performed using the four DoP forms described above at the minimum surface elevation angle of 5° over the global region. Plots compare the mean of the full set (equivalent to what was performed in ref. 5) with the longitude points over all the latitude parallels. Tabulated data compare the performance of the full set of data with the SA of the limited set of data along the 0° longitude. Also, a variance of the subset of longitude points for all latitude parallels is plotted and tabulated. As the variance increases, the stability of the solution along a single longitude decreases.

TABLE 3.—NAVIGATION SIGNAL ASSUMPTIONS

Frequency used for Doppler measurements, GHz	GPS L1 (1.57545)
User range error (URE), m	1
User range-rate error (URRE), mm/sec	0.1

Latitude Study Simulation

The lunar surface was previously defined over a discrete set of 554 points on the surface (ref. 5). The latitude study examines a set of points in which the latitude separation is 0.05° increments along a single lunar meridian (0° E.). The analysis is performed over the duration of 1 lunar sidereal month (27.3 Earth days) where DoPs are calculated at an epoch rate of 5 min. The computations are performed using the four DoP forms described above at the minimum surface three elevation angle of 5° over the global region. Plots show the performance of the extended latitude data set for the two constellations for all the DoP forms and the three integration periods. Tabulated data compare the performance of the extended latitude data set with that of the original analysis.

Elevation Study Simulation

The previous lunar surface analysis was performed over three distinct minimum user elevation angles: 5°, 10°, and 15°. The elevation study examines the full range of minimum user elevation angles from 0° to 90°. The analysis is performed over the duration of 1 lunar sidereal month (27.3 Earth days) where DoPs are calculated at an epoch rate of 5 min. The computations are performed using the four DoP forms described above for the three integration periods over the global region. Plots show the results of the performance of the elevation study for both constellations. Tabulated data list the elevation angle for which the performance drops below the 90-, 50-, and 10-percent SA levels.

Modified Failure Mode Study Simulation

The modified failure mode study examines the effect of repositioning the satellites in the orbital plane in which the failure occurs. In the previous study, the failure mode analysis assumed that all the satellites would remain in the respective positions, creating a hole in the coverage. However, the present study examines the effect of attempting to fill the coverage gap by shifting the satellites in the orbital plane. The analysis is performed over the duration of 1 lunar sidereal month (27.3 Earth days) where DoPs are calculated at an epoch rate of 5 min. The computations are performed using the four DoP forms described above for the three minimum user elevation angles (5°, 10°, and 15°) for the three integration periods over the global region. Plots show the results of the performance of the modified failure mode constellations utilizing the SA metric. Tabulated data provide a comparison of the performance of the modified failure mode constellations with the nonfailure mode constellations and the failure mode nonmodified constellations.

Results

Results are presented for the four studies. The longitude study results section provides tables listing the system availability performance of the two constellations for the four types of DoP with the full set of data points and the single longitude set of data points. Also, the variance of the system availability results along latitude parallels is tabulated. The latitude study results section provides a tabulated summary of the differences in the system availability performance when utilizing 7.5° and 0.05° spacing between points. The elevation study results section provides a tabulated list of the elevation angle for which the performance drops below the 90-percent system availability level. Finally, the study results section for the modified failure mode provides tables listing changes in the performance when three modes are utilized for both constellations of interest: the normal, the failure, and the modified failure.

Longitude Study

This section presents the results of the longitude study. A listing of the system availability performance with the full set of data points and the single longitude set of data points is provided in table 4. The notation for the mean performance of all the longitudes is labeled “Mean *C*,” where *C* is the constellation of interest. The notation for the performance of the 0° longitude set of points is labeled “Single *C*,” where *C* is the constellation of interest. Results are listed for the four types of DoP for each of the satellite constellations along the multiple integration periods: kinematic (0 latency), 15 min, or 1 hr.

The variance of the system availability results along latitude parallels is tabulated in table 5. Results are listed for the four types of DoP for each of the two satellite constellations along the multiple integration periods: kinematic (0 latency), 15 min, or 1 hr.

Appendix A contains plots for the system availability comparison of all the longitudes with the mean of the longitudes, as well as a comparison of the plots of the system availability variance. Results have shown that the mean of the performance along the different longitudes is the same as the prior evaluation of the performance. For the single longitude performance, there are very small changes in performance as compared with the mean of the single longitude performances. This finding is verified by the system availability variance results, which show that the variance of the single longitudes along the different latitude parallels is small. The overall conclusion of this study is that since the system availability is computed over a lunar sidereal month, the error associated with limiting the study to a single longitude of interest is negligible. Therefore, if this type of study had to be performed again in the future for a different satellite constellation, it is believed that the overall global performance could be extracted from evaluating along a single longitude of interest.

Latitude Study

This section presents the results of the latitude study. A listing of the differences between the system availability performance along the 0° longitude for the 7.5° and the 0.05° latitude

TABLE 4.—LONGITUDE STUDY SYSTEM AVAILABILITY COMPARISON

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Mean Pol 8/2/1 SMA 9250	87.32	96.22	98.41
	Single Pol 8/2/1 SMA 9250	87.36	96.23	98.41
	Mean Pol 6/2/1 SMA 9250	79.02	90.69	93.20
	Single Pol 6/2/1 SMA 9250	79.03	90.69	93.20
HTDoP	Mean Pol 8/2/1 SMA 9250	96.51	99.67	99.97
	Single Pol 8/2/1 SMA 9250	96.54	99.67	99.97
	Mean Pol 6/2/1 SMA 9250	90.00	99.28	99.91
	Single Pol 6/2/1 SMA 9250	90.01	99.28	99.91
PDoP	Mean Pol 8/2/1 SMA 9250	90.19	96.77	99.17
	Single Pol 8/2/1 SMA 9250	90.23	96.76	99.18
	Mean Pol 6/2/1 SMA 9250	87.30	92.82	97.02
	Single Pol 6/2/1 SMA 9250	87.30	92.81	97.00
HDoP	Mean Pol 8/2/1 SMA 9250	98.78	99.73	99.98
	Single Pol 8/2/1 SMA 9250	98.82	99.72	99.98
	Mean Pol 6/2/1 SMA 9250	97.65	99.47	99.96
	Single Pol 6/2/1 SMA 9250	97.64	99.44	99.95

TABLE 5.—LONGITUDE STUDY SYSTEM AVAILABILITY VARIANCE COMPARISON

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	0.0114	0.0029	0.0018
	Pol 6/2/1 SMA 9250	.0121	.0121	.0166
HTDoP	Pol 8/2/1 SMA 9250	0.0065	0.0003	0.0021
	Pol 6/2/1 SMA 9250	.0125	.0031	.0007
PDoP	Pol 8/2/1 SMA 9250	0.0106	0.0023	0.0004
	Pol 6/2/1 SMA 9250	.0109	.0075	.0057
HDoP	Pol 8/2/1 SMA 9250	0.0094	0.0084	0.0015
	Pol 6/2/1 SMA 9250	.0179	.0173	.0018

TABLE 6.—LATITUDE STUDY SYSTEM AVAILABILITY DIFFERENCE

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	–0.19	–0.04	–0.05
	Pol 6/2/1 SMA 9250	–.16	–.17	–.19
HTDoP	Pol 8/2/1 SMA 9250	–0.01	–0.02	–0.01
	Pol 6/2/1 SMA 9250	–.16	–.06	–.01
PDoP	Pol 8/2/1 SMA 9250	–0.20	–0.02	–0.03
	Pol 6/2/1 SMA 9250	–.17	–.20	–.07
HDoP	Pol 8/2/1 SMA 9250	–.09	0.00	0.00
	Pol 6/2/1 SMA 9250	–.18	.00	.01

spacing is presented in table 6. Results are listed for the four types of DoP for each of the satellite constellations along the multiple integration periods, listed as kinematic (0 latency), 15 min, or 1 hr. Negative numbers mean that the 0.05° latitude spacing had larger system availability than the 7.5° latitude spacing.

Appendix B contains plots of the availability for the 0.05° latitude spacing along the 0° longitude. Note that the data used to compute the system availability for the 7.5° latitude spacing is just a subset of the points in the 0.05° latitude spacing. Results have shown that there are small discrepancies in the expanded data set of 0.05° latitude spacing and the previously used 7.5° latitude spacing. The overall conclusion of this study is that the previous latitude spacing of 7.5° is adequate for an analysis of this type of DoP-based stationary surface navigation problem.

Elevation Study

This section presents the results of the elevation study. Tables 7 through 9 provide a listing of the largest integer elevation angle for which the system availability is still above 90, 50, and 10 percent, respectively. Results are listed for the four types of DoP for each of the satellite constellations along the multiple integration periods: kinematic (0 latency), 15 min, or 1 hr.

Appendix C contains curves of the system availability of the two satellite constellations versus integer elevation angles between 0° and 90°. Results shown above in tables 7 through 9 list the largest elevation angles for which the system availability is still above 90, 50, and 10 percent, respectively. Information in the tables illustrates that (a) the two constellations will perform with unknown elevation angle restrictions on visibility and (b) the polar 8/2/1 SMA 9250 constellation can withstand a larger elevation angle to maintain the same level of performance. This means that the polar 8/2/1 SMA 9250 constellation can withstand a smaller visibility to the surface users. This information can be important when operating near craters or areas on the lunar surface for which little information is known with regard to the elevation angles of obstacles that block line-of-sight visibility.

TABLE 7.—ELEVATION STUDY FOR 90-PERCENT ELEVATION LEVEL

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	3	11	15
	Pol 6/2/1 SMA 9250	NA	5	7
HTDoP	Pol 8/2/1 SMA 9250	11	36	41
	Pol 6/2/1 SMA 9250	4	27	32
PDoP	Pol 8/2/1 SMA 9250	5	15	31
	Pol 6/2/1 SMA 9250	3	8	21
HDoP	Pol 8/2/1 SMA 9250	32	37	42
	Pol 6/2/1 SMA 9250	22	28	33

TABLE 8.—ELEVATION STUDY FOR 50-PERCENT ELEVATION LEVEL

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	22	28	32
	Pol 6/2/1 SMA 9250	17	21	24
HTDoP	Pol 8/2/1 SMA 9250	28	52	57
	Pol 6/2/1 SMA 9250	20	47	52
PDoP	Pol 8/2/1 SMA 9250	26	40	50
	Pol 6/2/1 SMA 9250	20	34	44
HDoP	Pol 8/2/1 SMA 9250	49	53	58
	Pol 6/2/1 SMA 9250	44	51	53

TABLE 9.—ELEVATION STUDY FOR 10-PERCENT ELEVATION LEVEL

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	42	49	53
	Pol 6/2/1 SMA 9250	36	42	46
HTDoP	Pol 8/2/1 SMA 9250	46	73	77
	Pol 6/2/1 SMA 9250	39	71	75
PDoP	Pol 8/2/1 SMA 9250	46	63	71
	Pol 6/2/1 SMA 9250	39	59	69
HDoP	Pol 8/2/1 SMA 9250	70	74	78
	Pol 6/2/1 SMA 9250	67	72	76

Modified Failure Mode Study

This section presents results for the modified failure mode study. Tables 10 through 12 provide system availability results for the three minimum user elevation angles, respectively. Results are listed for the four types of DoP along the multiple integration periods: kinematic (0 latency), 15 min, or 1 hr. The satellite constellations are for the polar 8/2/1 SMA 9250, which, for example, are written as Pol 8/2/1 SMA 9250, Mod Pol 8/2/1 SMA 9250, and Fail Pol 8/2/1 SMA 9250. Pol 8/2/1 SMA 9250 is the standard eight-satellite polar constellation. Mod Pol 8/2/1 SMA 9250 is the modified failure mode of the standard eight-satellite polar constellation. This constellation has seven satellites where the orbital plane with three satellites has been reoriented to create even spacing between all the satellites. Fail Pol 8/2/1 SMA 9250 is the failure mode of the standard eight-satellite polar constellation. This constellation also has seven satellites; however, the orbital plane with three satellites has not been reoriented to create even spacing but has a gap where the failure satellite was previously located. The naming for the polar 6/2/1 SMA 9250 is similar to that for the polar 8/2/1 SMA 9250.

Appendix D contains plots of system availabilities for the three variations of each of the lunar constellations (normal, modified failure, and failure modes). Each constellation on each image is superimposed on a grayscale image of the Moon's surface with the center of the image being the latitude/longitude pair of (0° N., 0° E.). The black colors on the superimposed system availabilities denote 0 percent. However, as the colors move from black, to red, to yellow, to white, the system availabilities go up to 100 percent.

Tables 10 through 12 show some interesting results that are constellation dependent. For the polar 8/2/1 constellation, the performance of the Mod Pol 8/2/1 constellation is always less than that of the polar 8/2/1 and is also always greater than for the Fail Pol 8/2/1. The same cannot be said about the polar 6/2/1 constellation. In kinematic cases, the Mod Pol 6/2/1 constellation sometimes performs worse than the Fail Pol 6/2/1. When integrating the solution, however, the Mod Pol 6/2/1 constellation outperforms the Fail Pol 6/2/1.

TABLE 10.—MODIFIED FAILURE MODE STUDY FOR 5° ELEVATION ANGLE

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	87.32	96.22	98.41
	Mod Pol 8/2/1 SMA 9250	80.88	93.94	96.22
	Fail Pol 8/2/1 SMA 9250	75.56	88.57	94.97
	Pol 6/2/1 SMA 9250	79.02	90.69	93.20
	Mod Pol 6/2/1 SMA 9250	48.91	73.08	82.24
	Fail Pol 6/2/1 SMA 9250	56.57	68.27	77.23
HTDoP	Pol 8/2/1 SMA 9250	96.51	99.67	99.97
	Mod Pol 8/2/1 SMA 9250	93.89	99.47	99.94
	Fail Pol 8/2/1 SMA 9250	90.48	99.09	99.71
	Pol 6/2/1 SMA 9250	90.00	99.28	99.91
	Mod Pol 6/2/1 SMA 9250	72.10	97.98	99.35
	Fail Pol 6/2/1 SMA 9250	68.90	97.39	98.67
PDoP	Pol 8/2/1 SMA 9250	90.19	96.77	99.17
	Mod Pol 8/2/1 SMA 9250	88.98	95.09	98.19
	Fail Pol 8/2/1 SMA 9250	83.22	94.39	98.19
	Pol 6/2/1 SMA 9250	87.30	92.82	97.02
	Mod Pol 6/2/1 SMA 9250	69.31	87.25	95.11
	Fail Pol 6/2/1 SMA 9250	65.21	85.90	94.13
HDoP	Pol 8/2/1 SMA 9250	98.78	99.73	99.98
	Mod Pol 8/2/1 SMA 9250	98.19	99.60	99.97
	Fail Pol 8/2/1 SMA 9250	97.83	99.28	99.78
	Pol 6/2/1 SMA 9250	97.65	99.47	99.96
	Mod Pol 6/2/1 SMA 9250	95.60	98.44	99.49
	Fail Pol 6/2/1 SMA 9250	95.10	97.88	98.84

TABLE 11.—MODIFIED FAILURE MODE STUDY FOR 10° ELEVATION ANGLE

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	79.04	91.81	95.62
	Mod Pol 8/2/1 SMA 9250	70.25	87.98	92.08
	Fail Pol 8/2/1 SMA 9250	65.96	81.31	89.77
	Pol 6/2/1 SMA 9250	69.38	82.53	87.29
	Mod Pol 6/2/1 SMA 9250	38.52	61.43	71.48
	Fail Pol 6/2/1 SMA 9250	48.00	59.05	68.23
HTDoP	Pol 8/2/1 SMA 9250	92.17	99.49	99.95
	Mod Pol 8/2/1 SMA 9250	87.73	99.26	99.92
	Fail Pol 8/2/1 SMA 9250	83.02	98.41	99.36
	Pol 6/2/1 SMA 9250	81.11	99.08	99.89
	Mod Pol 6/2/1 SMA 9250	59.76	96.38	98.45
	Fail Pol 6/2/1 SMA 9250	58.36	95.85	97.66
PDoP	Pol 8/2/1 SMA 9250	84.19	93.97	98.26
	Mod Pol 8/2/1 SMA 9250	82.08	91.65	97.01
	Fail Pol 8/2/1 SMA 9250	74.75	90.61	96.54
	Pol 6/2/1 SMA 9250	78.45	88.59	95.56
	Mod Pol 6/2/1 SMA 9250	57.57	81.06	92.07
	Fail Pol 6/2/1 SMA 9250	55.44	80.47	91.42
HDoP	Pol 8/2/1 SMA 9250	98.16	99.58	99.96
	Mod Pol 8/2/1 SMA 9250	97.49	99.45	99.96
	Fail Pol 8/2/1 SMA 9250	96.61	98.65	99.43
	Pol 6/2/1 SMA 9250	96.99	99.37	99.95
	Mod Pol 6/2/1 SMA 9250	93.32	97.04	98.66
	Fail Pol 6/2/1 SMA 9250	92.97	96.46	97.84

TABLE 12.—MODIFIED FAILURE MODE STUDY FOR 15° ELEVATION ANGLE

DoP type	Constellation	Integration period		
		Kinematic	15 min	1 hr
GDoP	Pol 8/2/1 SMA 9250	68.10	84.47	90.57
	Mod Pol 8/2/1 SMA 9250	57.29	78.28	85.17
	Fail Pol 8/2/1 SMA 9250	55.07	71.84	81.94
	Pol 6/2/1 SMA 9250	57.18	69.99	77.88
	Mod Pol 6/2/1 SMA 9250	28.90	48.90	59.15
	Fail Pol 6/2/1 SMA 9250	38.54	48.10	57.54
HTDoP	Pol 8/2/1 SMA 9250	84.95	99.22	99.92
	Mod Pol 8/2/1 SMA 9250	77.71	98.92	99.87
	Fail Pol 8/2/1 SMA 9250	73.19	97.28	98.68
	Pol 6/2/1 SMA 9250	67.53	98.64	99.83
	Mod Pol 6/2/1 SMA 9250	46.48	93.67	96.84
	Fail Pol 6/2/1 SMA 9250	46.18	93.39	95.99
PDoP	Pol 8/2/1 SMA 9250	76.44	90.06	96.94
	Mod Pol 8/2/1 SMA 9250	72.17	86.90	95.30
	Fail Pol 8/2/1 SMA 9250	64.86	85.55	94.28
	Pol 6/2/1 SMA 9250	65.84	83.11	93.53
	Mod Pol 6/2/1 SMA 9250	45.31	73.61	88.13
	Fail Pol 6/2/1 SMA 9250	44.61	73.69	87.76
HDoP	Pol 8/2/1 SMA 9250	97.25	99.39	99.95
	Mod Pol 8/2/1 SMA 9250	96.41	99.24	99.94
	Fail Pol 8/2/1 SMA 9250	94.80	97.64	98.80
	Pol 6/2/1 SMA 9250	95.70	99.16	99.94
	Mod Pol 6/2/1 SMA 9250	89.70	94.60	97.16
	Fail Pol 6/2/1 SMA 9250	89.70	94.25	96.25

The reason for the degraded performance of the Mod Pol 6/2/1 constellation versus that of the Fail Pol 6/2/1 constellation involves the orientation of the satellites in the failure mode orbital plane. In the modified constellation, the spacing between the two satellites in the failure mode orbital plane is 180° and 180°. However, in the failure mode constellation, the spacing between the two satellites in the failure mode orbital plane is 120° and 240°. These spacings result in a smaller angular separation during certain intervals for the failure mode of the polar 6/2/1 constellation. Decreasing angular separation, in particular from 180° to 120°, means that the surface user may be able to view each of the satellites, which has the effect of increasing overall visibility. Otherwise, when the angular separation is 180°, only one of the two possible satellites could be viewed instantaneously. These results show that in the event of the failure of a satellite, the fixed integration period must be taken into account along with the orbital characteristics of the satellite constellation before transitioning the constellation into equal phasing.

Conclusions

The four studies discussed in this report have produced some interesting results. The longitude study showed that when the simulation is performed over a lunar sidereal month and a time average of availability is used, lunar constellations can be evaluated over a single longitude with little impact on results. This will lead to smaller computer simulation run times as the necessary amount of data points can be greatly reduced.

The latitude study showed that the spacing between the sampling points that was previously used as 7.5° is adequate because the reduced spacing of 0.05° creates comparable results. This spacing also aids in the reduction of the simulation run time, as smaller amounts of latitude points must be utilized to assess lunar constellation performance for stationary surface users.

Elevation study results confirmed that performance degrades with the increase in the minimum elevation angle and therefore the loss in visibility. It was known prior to the present study that performance at a 15° elevation angle was lower than at a 10° elevation angle and that a 10° elevation angle had a lower performance than a 5° elevation angle. What was not known was whether performance increased with an increase in elevation angle at some point. The answer is that system availability is a monotonically decreasing function with elevation angle. The implications of this finding are that if lunar surface users need to obtain a position fix, it is in their best interest to obtain such a fix in a location that has the least amount of obstacles to block visibility.

The modified failure mode study showed that reorienting the satellites in a failure orbit plane does not necessarily increase system performance. For the polar 6/2/1 constellation operating in kinematic mode, the system availability metric is larger for the failure mode version of the constellation than for the modified failure mode of the constellation when operating in one-way mode without terrain information. However, for the polar 8/2/1 constellation, performance always increases when transitioning from the failure mode to the modified failure mode. Note that in all cases, performance is still not as good as that in the nonfailure mode of operation for either satellite constellation.

Appendix A—Longitude Study

A.1 System Availability Comparisons

All figures in this section are described as follows: the solid blue line connects the mean longitude performance from each of the latitudes versus the system availability for the polar 8/2/1 constellation; the black line serves the same purpose for the polar 6/2/1 constellation; red dots indicate all the individual longitude performance levels at each latitude for the polar 8/2/1 constellation; green dots serve the same purpose for the polar 6/2/1 constellation.

A.1.1 GDoP kinematic results

Figure A.1.1.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with kinematic measurements.

A.1.2 GDoP dynamic 15-min results

Figure A.1.2.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 15-min dynamic measurements.

A.1.3 GDoP dynamic 1-hr results

Figure A.1.3.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 1-hr dynamic measurements.

A.1.4 HTDoP kinematic results

Figure A.1.4.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with kinematic measurements.

A.1.5 HTDoP dynamic 15-min results

Figure A.1.5.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 15-min dynamic measurements.

A.1.6 HTDoP dynamic 1-hr results

Figure A.1.6.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 1-hr dynamic measurements.

A.1.7 PDoP kinematic results

Figure A.1.7.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with kinematic measurements.

A.1.8 PDoP dynamic 15-min results

Figure A.1.8.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 15-min dynamic measurements.

A.1.9 PDoP dynamic 1-hr results

Figure A.1.9.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 1-hr dynamic measurements.

A.1.10 HDoP kinematic results

Figure A.1.10.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with kinematic measurements.

A.1.11 HDoP dynamic 15-min results

Figure A.1.11.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 15-min dynamic measurements.

A.1.12 HDoP dynamic 1-hr results

Figure A.1.12.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 1-hr dynamic measurements.

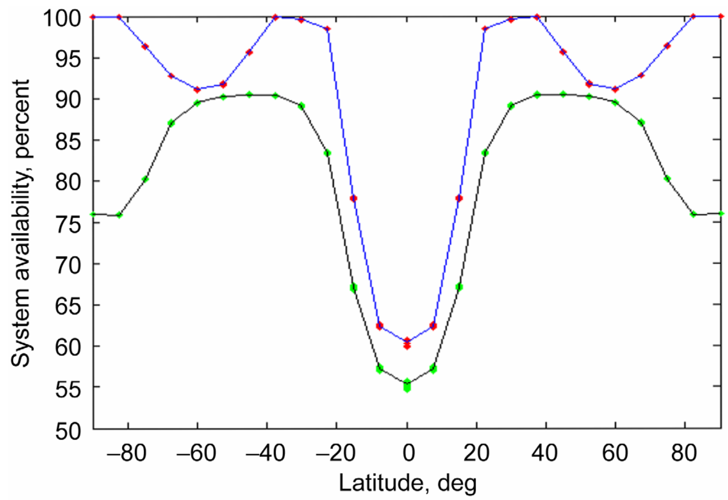

Figure A.1.1.1.—GDoP kinematic system availability performance for no terrain, one-way operation.

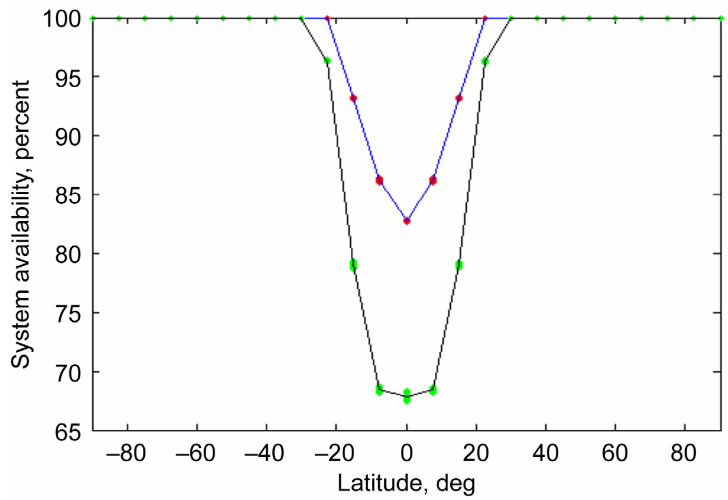

Figure A.1.2.1.—GDoP 15-min dynamic system availability performance for no terrain, one-way operation.

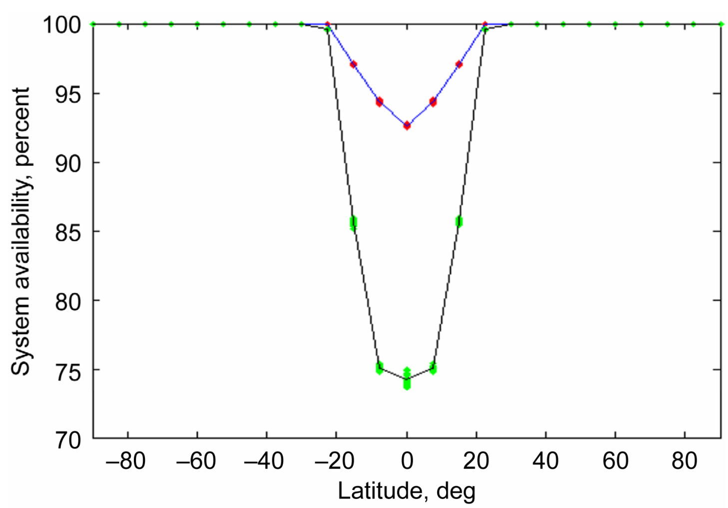

Figure A.1.3.1.—GDoP 1-hr dynamic system availability performance for no terrain, one-way operation.

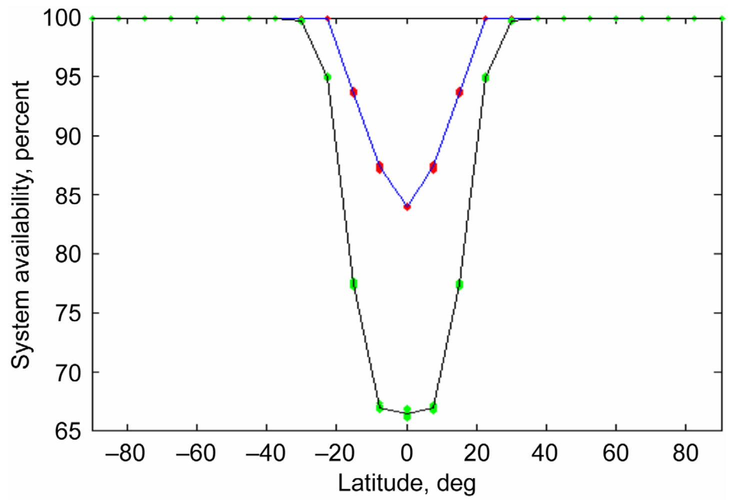

Figure A.1.4.1.—HTDoP kinematic system availability performance for good terrain, one-way operation.

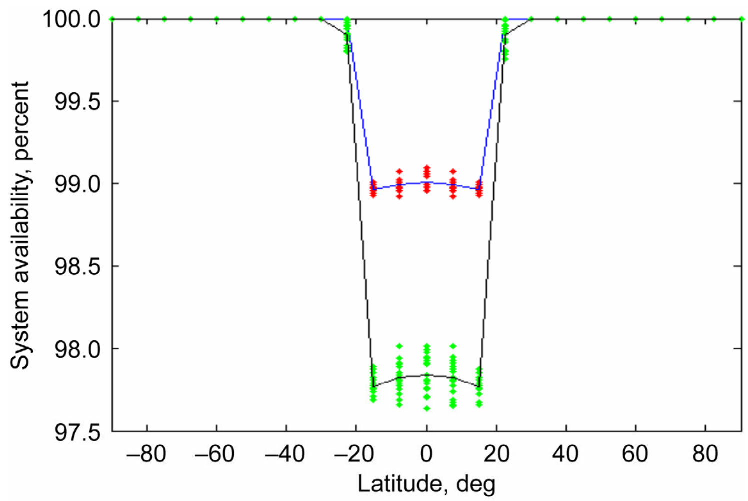

Figure A.1.5.1.—HTDoP 15-min dynamic system availability performance for good terrain, one-way operation.

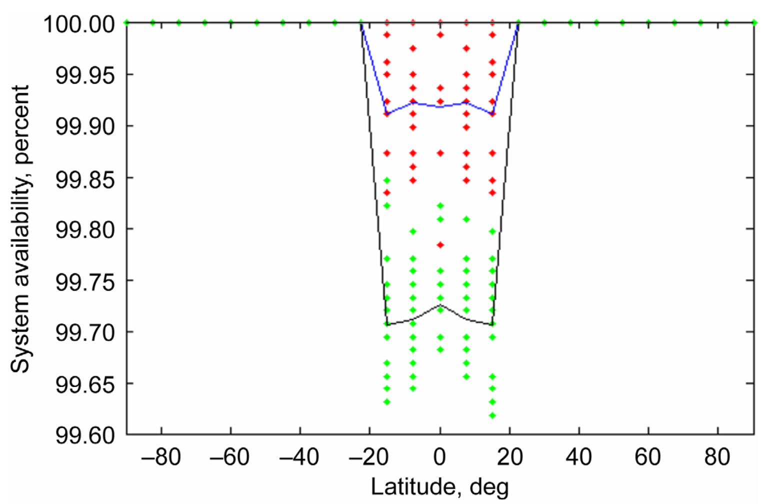

Figure A.1.6.1.—HTDoP 1-hr dynamic system availability performance for good terrain, one-way operation.

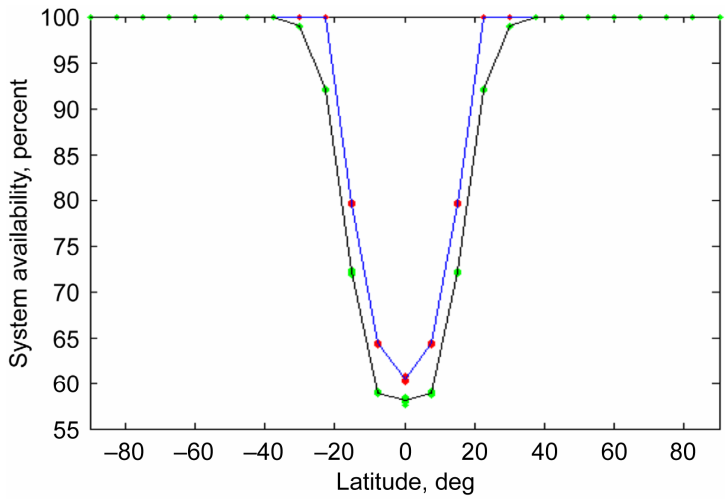

Figure A.1.7.1.—PDoP kinematic system availability performance for no terrain, two-way operation.

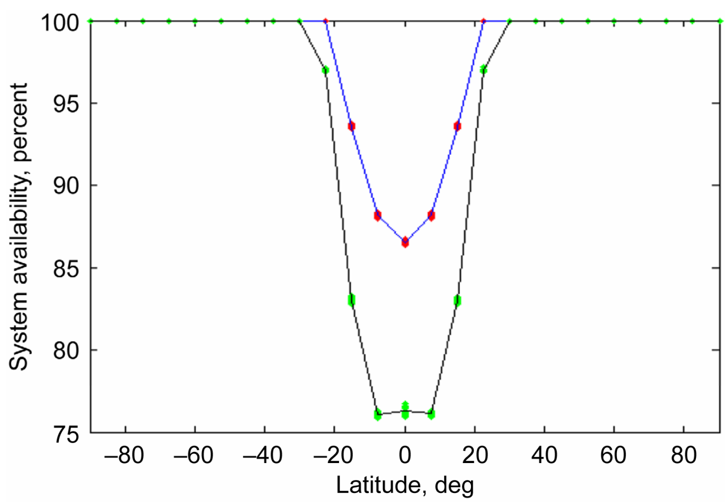

Figure A.1.8.1.—PDoP 15-min dynamic system availability performance for no terrain, two-way operation.

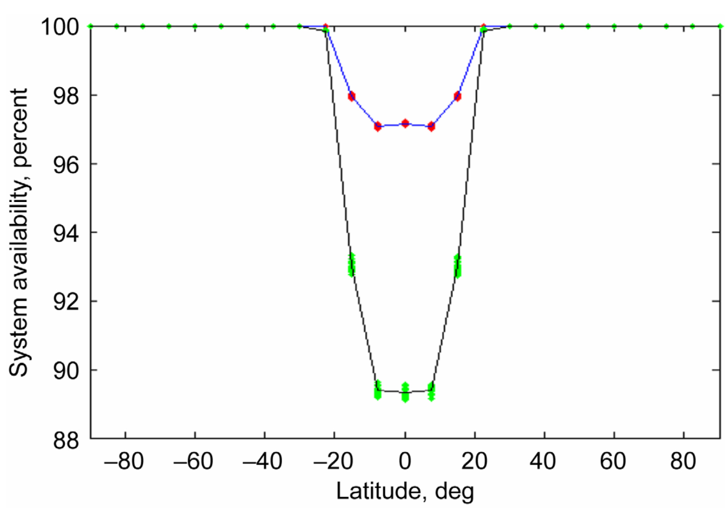

Figure A.1.9.1.—PDoP 1-hr dynamic system availability performance for no terrain, two-way operation.

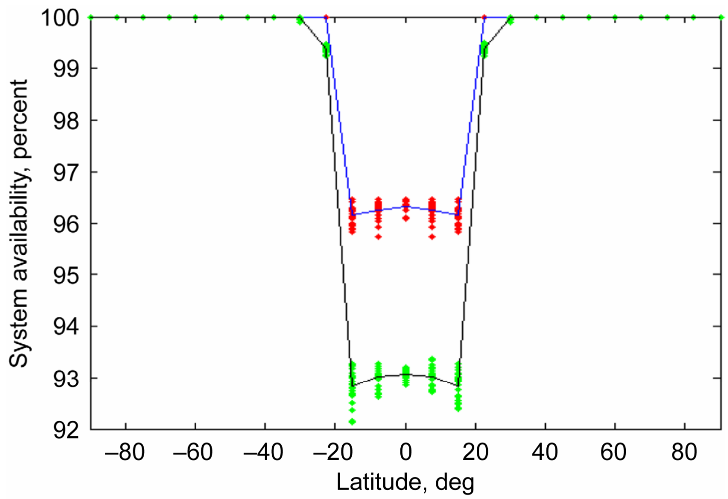

Figure A.1.10.1.—HDoP kinematic system availability performance for good terrain, two-way operation.

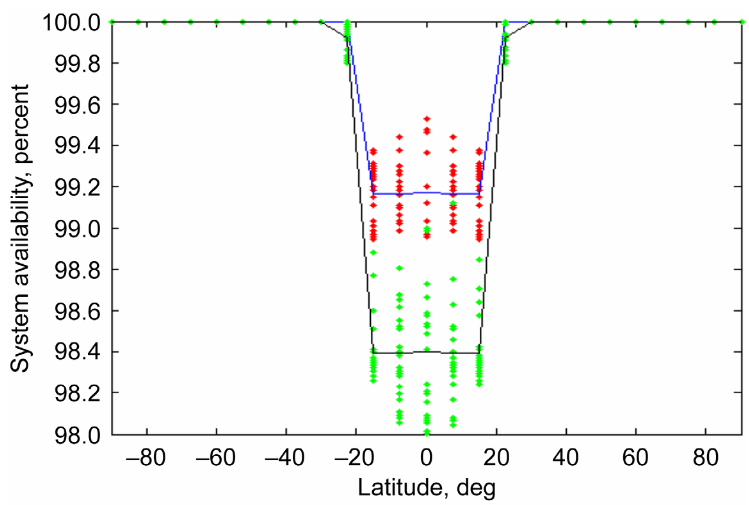

Figure A.1.11.1.—HDoP 15-min dynamic system availability performance for good terrain, two-way operation.

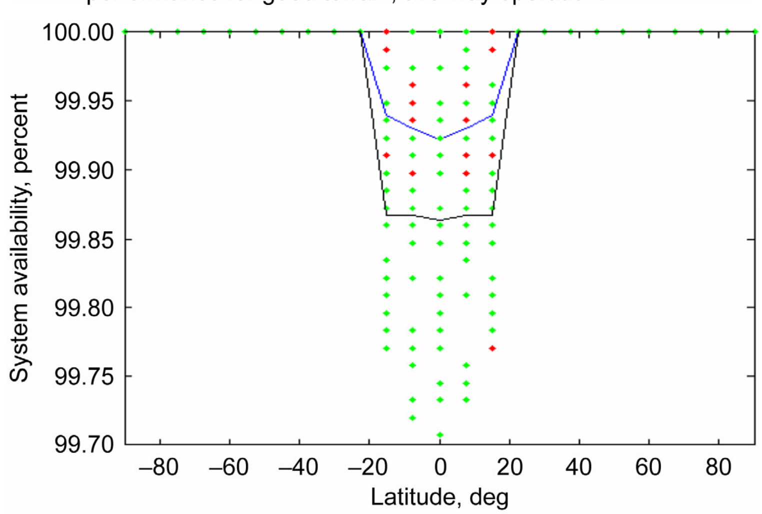

Figure A.1.12.1.—HDoP 1-hr dynamic system availability performance for good terrain, two-way operation.

A.2 Variance Comparisons

All figures in this section are described as follows: the solid blue line connects the variance of the longitude performance from each of the latitudes versus the availability variance for the polar 8/2/1 constellation, and the red line serves the same purpose for the polar 6/2/1 constellation.

A.2.1 GDoP kinematic results

Figure A.2.1.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with kinematic measurements.

A.2.2 GDoP dynamic 15-min results

Figure A.2.2.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 15-min dynamic measurements.

A.2.3 GDoP dynamic 1-hr results

Figure A.2.3.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 1-hr dynamic measurements.

A.2.4 HTDoP kinematic results

Figure A.2.4.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with kinematic measurements.

A.2.5 HTDoP dynamic 15-min results

Figure A.2.5.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 15-min dynamic measurements.

A.2.6 HTDoP dynamic 1-hr results

Figure A.2.6.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 1-hr dynamic measurements.

A.2.7 PDoP kinematic results

Figure A.2.7.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with kinematic measurements.

A.2.8 PDoP dynamic 15-min results

Figure A.2.8.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 15-min dynamic measurements.

A.2.9 PDoP dynamic 1-hr results

Figure A.2.9.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 1-hr dynamic measurements.

A.2.10 HDoP kinematic results

Figure A.2.10.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with kinematic measurements.

A.2.11 HDoP dynamic 15-min results

Figure A.2.11.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 15-min dynamic measurements.

A.2.12 HDoP dynamic 1-hr results

Figure A.2.12.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 1-hr dynamic measurements.

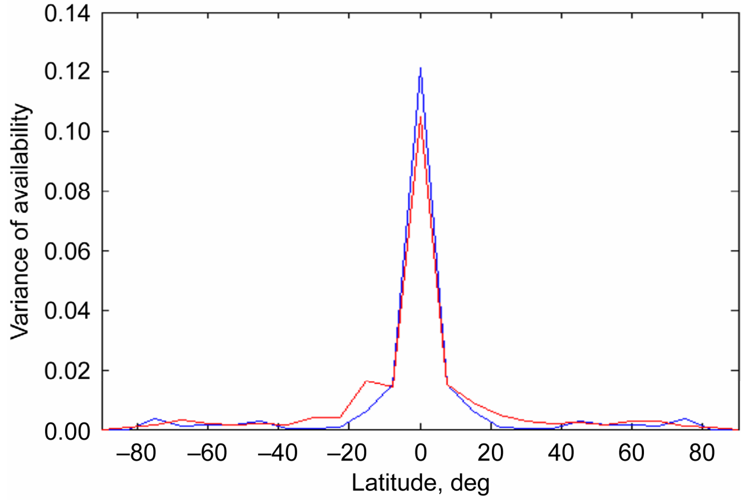

Figure A.2.1.1.—GDoP kinematic availability variance performance for no terrain, one-way operation.

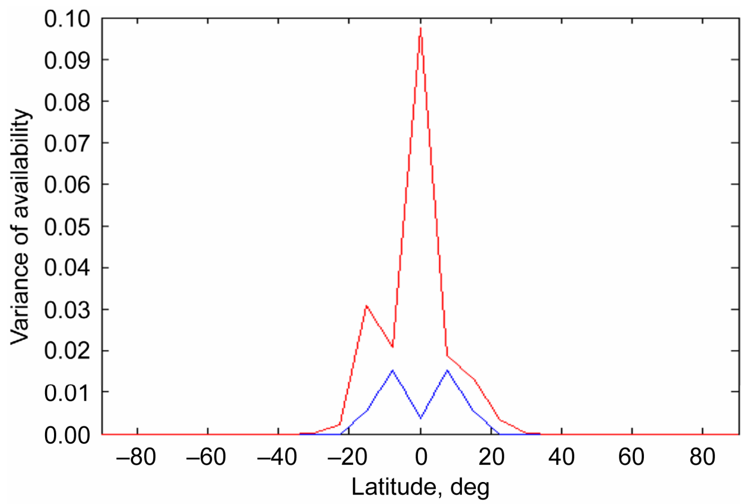

Figure A.2.2.1.—GDoP 15-min dynamic availability variance performance for no terrain, one-way operation.

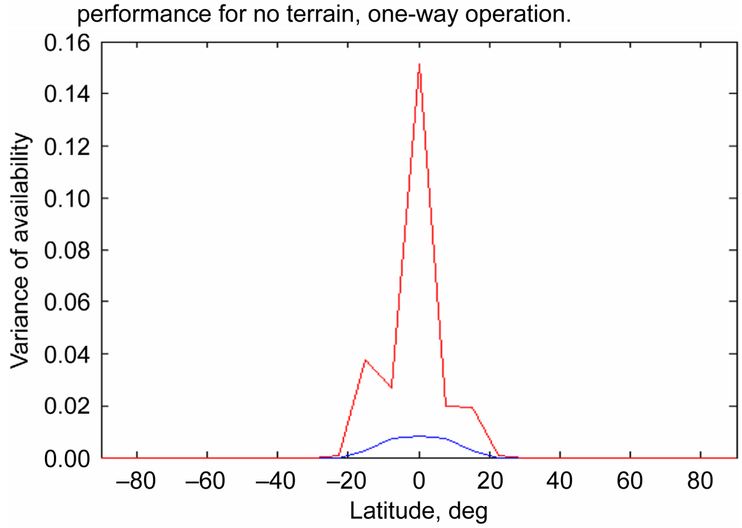

Figure A.2.3.1.—GDoP 1-hr dynamic availability variance performance for no terrain, one-way operation.

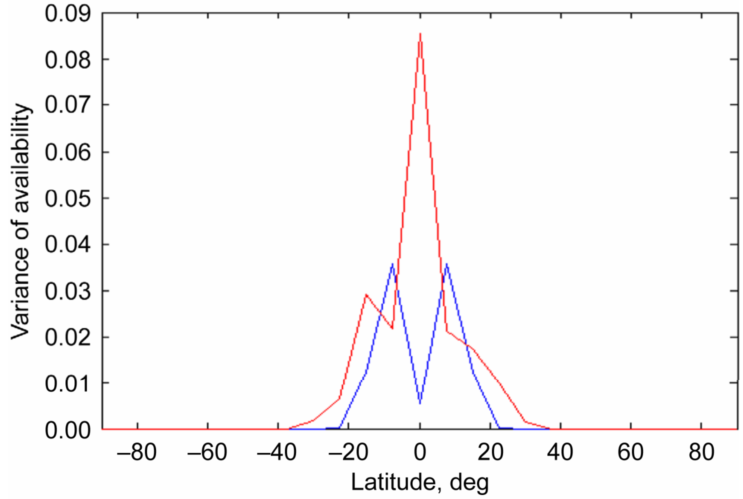

Figure A.2.4.1.—HTDoP kinematic availability variance performance for good terrain, one-way operation.

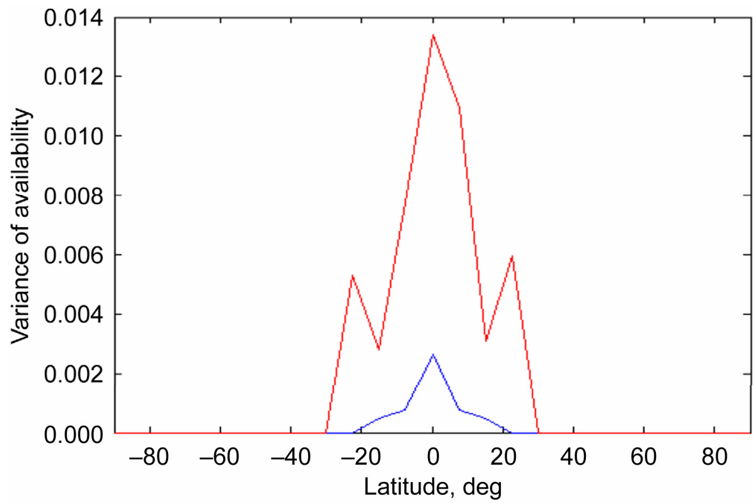

Figure A.2.5.1.—HTDoP 15-min dynamic availability variance performance for good terrain, one-way operation.

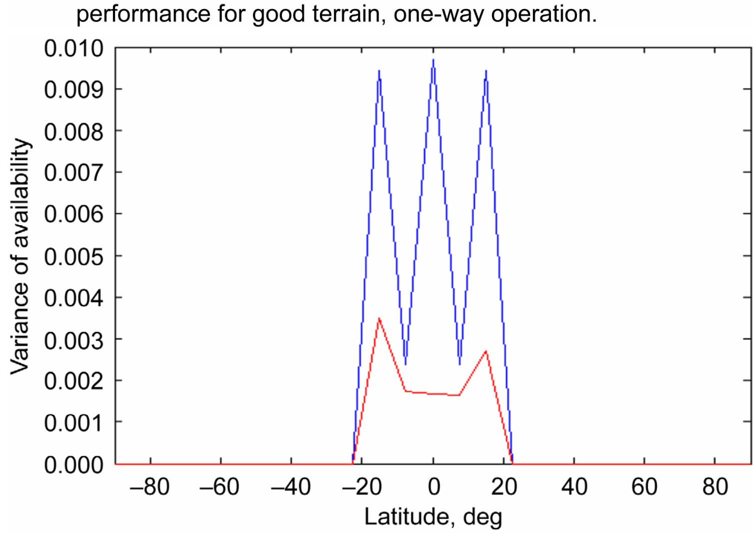

Figure A.2.6.1.—HTDoP 1-hr dynamic availability variance performance for good terrain, one-way operation.

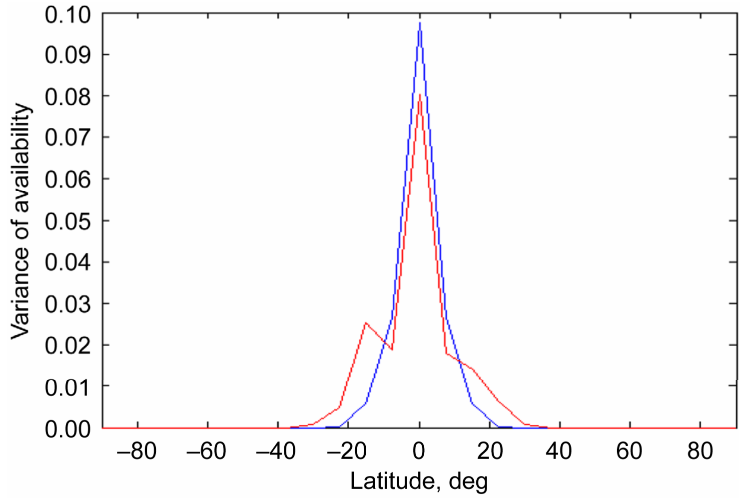

Figure A.2.7.1.—PDoP kinematic availability variance performance for no terrain, two-way operation.

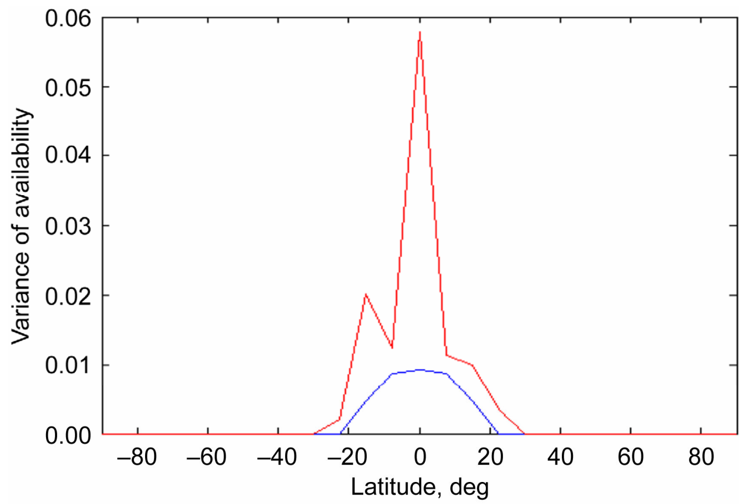

Figure A.2.8.1.—PDoP 15-min availability variance performance for no terrain, two-way operation.

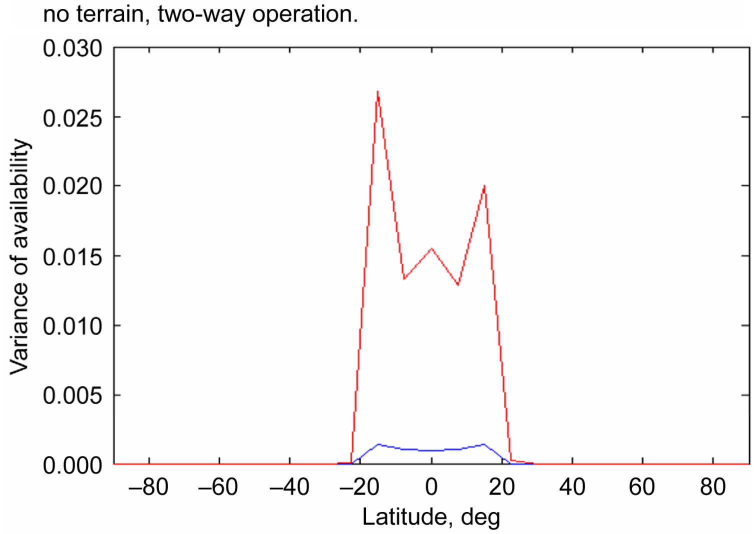

Figure A.2.9.1.—PDoP 1-hr dynamic availability variance performance for no terrain, two-way operation.

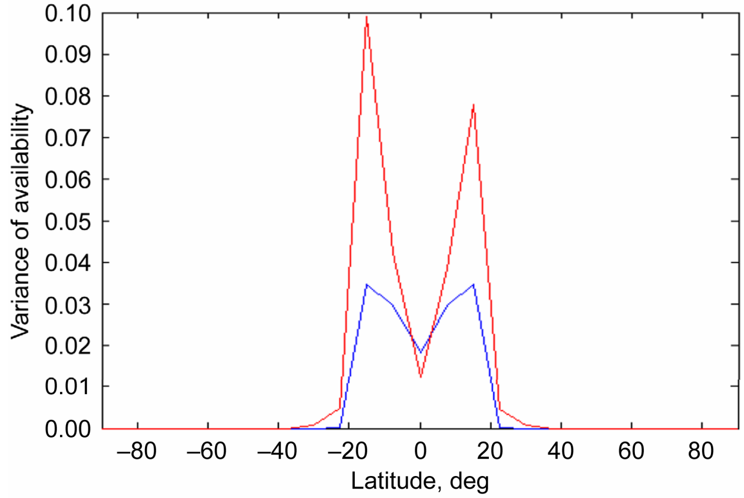

Figure A.2.10.1.—HDoP kinematic availability variance performance for good terrain, two-way operation.

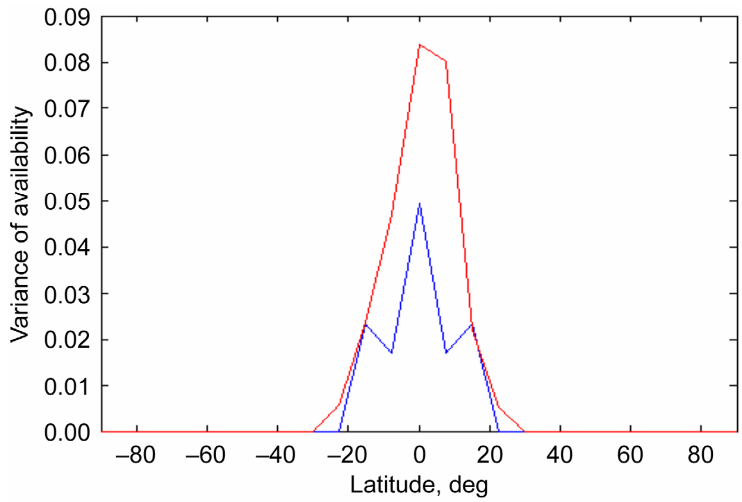

Figure A.2.11.1.—HDoP 15-min dynamic availability variance performance for good terrain, two-way operation.

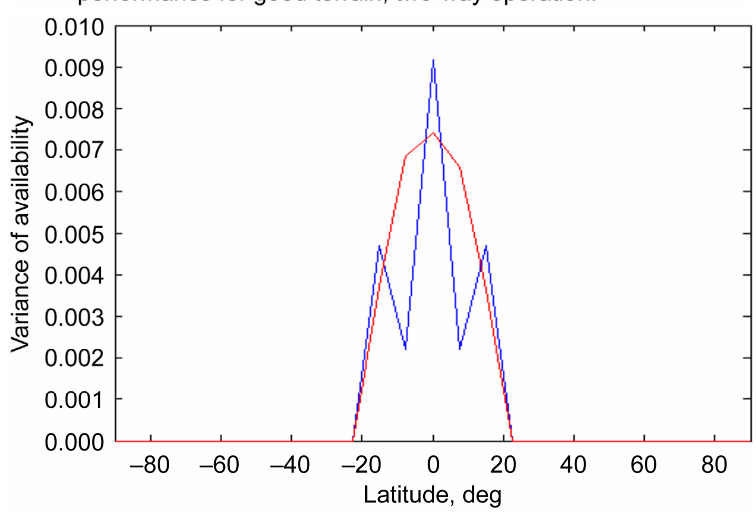

Figure A.2.12.1.—HDoP 1-hr dynamic availability variance performance for good terrain, two-way operation.

Appendix B—Latitude Study

All figures in appendix B are described as follows: the solid blue line connects the mean longitude availability performance from each of the latitudes versus the availability for the polar 8/2/1 constellation. The red line serves the same purpose for the polar 6/2/1 constellation.

B.1 GDoP kinematic results

Figure B.1.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with kinematic measurements.

B.2 GDoP dynamic 15-min results

Figure B.2.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 15-min dynamic measurements.

B.3 GDoP dynamic 1-hr results

Figure B.3.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 1-hr dynamic measurements.

B.4 HTDoP kinematic results

Figure B.4.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with kinematic measurements.

B.5 HTDoP dynamic 15-min results

Figure B.5.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 15-min dynamic measurements.

B.6 HTDoP dynamic 1-hr results

Figure B.6.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 1-hr dynamic measurements.

B.7 PDoP kinematic results

Figure B.7.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with kinematic measurements.

B.8 PDoP dynamic 15-min results

Figure B.8.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 15-min dynamic measurements.

B.9 PDoP dynamic 1-hr results

Figure B.9.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 1-hr dynamic measurements.

B.10 HDoP kinematic results

Figure B.10.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode of operation with terrain information and with kinematic measurements.

B.11 HDoP dynamic 15-min results

Figure B.11.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode of operation with terrain information and with 15-min dynamic measurements.

B.12 HDoP dynamic 1-hr results

Figure B.12.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode of operation with terrain information and with 1-hr dynamic measurements.

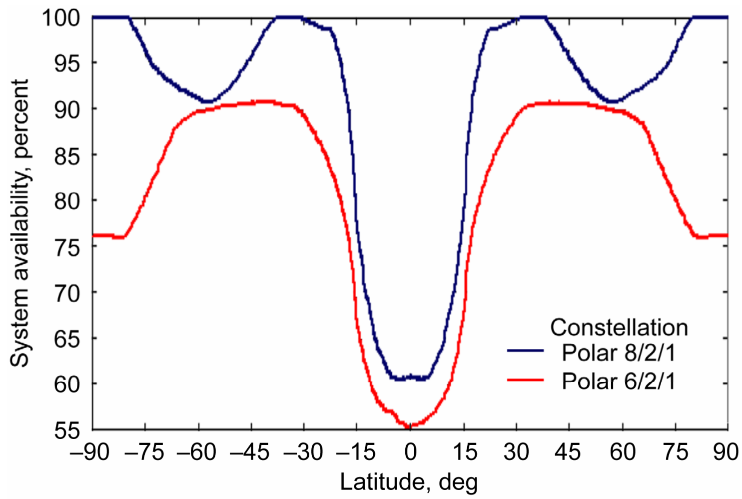

Figure B.1.1.—GDoP kinematic system availability performance for no terrain, one-way operation.

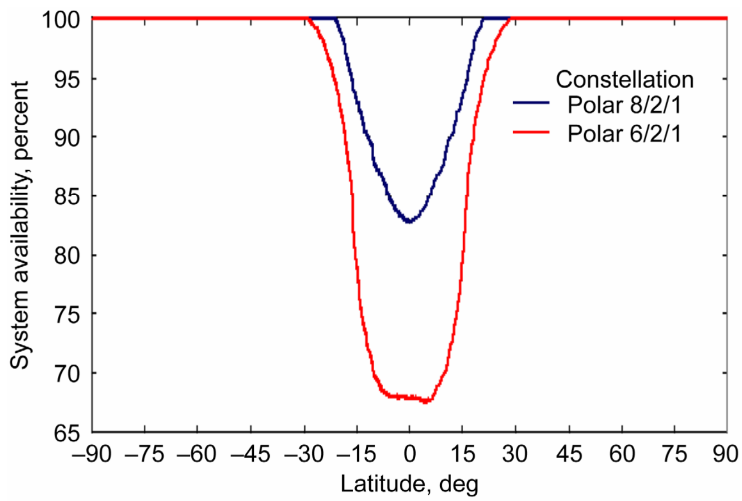

Figure B.2.1.—GDoP 15-min dynamic system availability performance for no terrain, one-way operation.

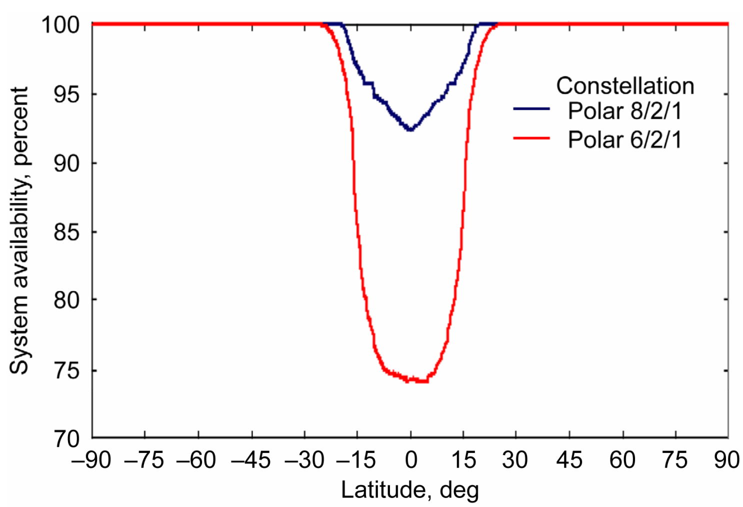

Figure B.3.1.—GDoP 1-hr dynamic system availability performance for no terrain, one-way operation.

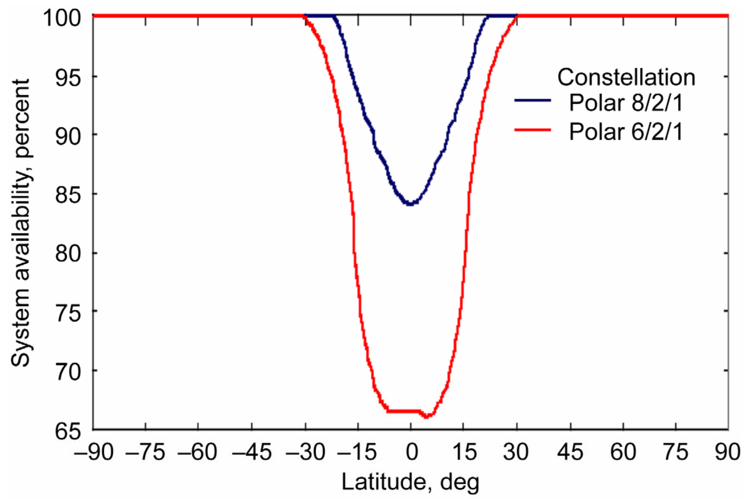

Figure B.4.1.—HTDoP kinematic system availability performance for good terrain, one-way operation.

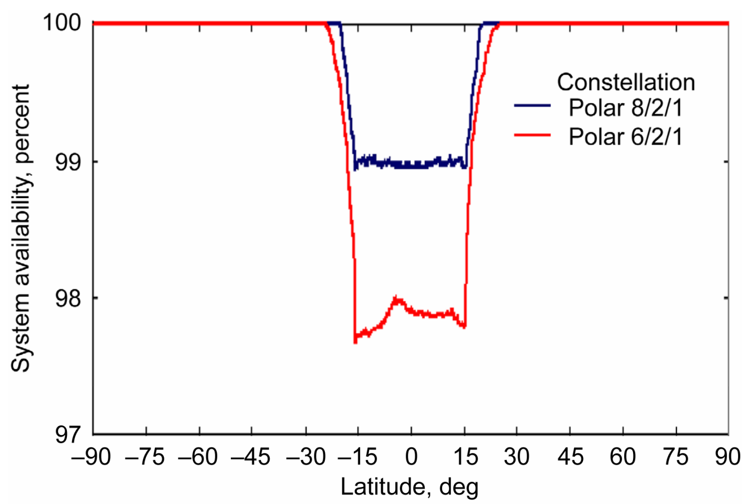

Figure B.5.1.—HTDoP 15-min dynamic system availability performance for good terrain, one-way operation.

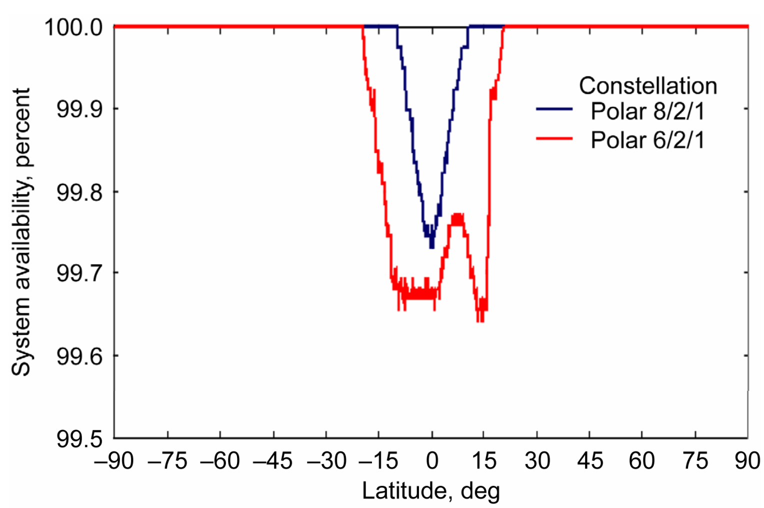

Figure B.6.1.—HTDoP 1-hr dynamic system availability performance for good terrain, one-way operation.

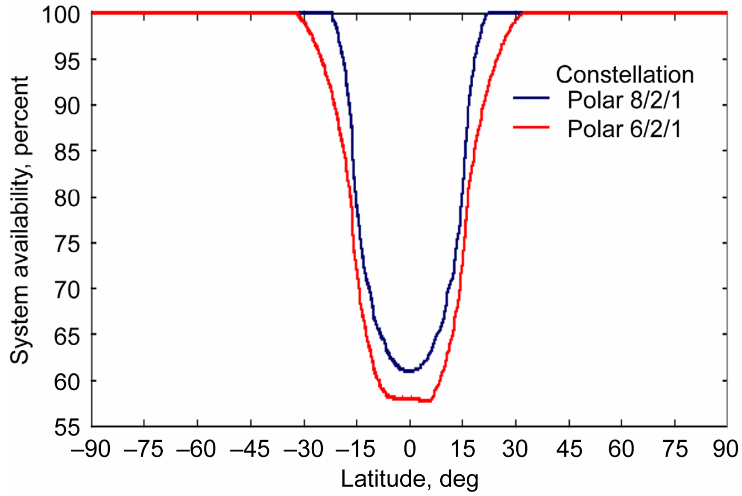

Figure B.7.1.—PDoP kinematic system availability performance for no terrain, two-way operation.

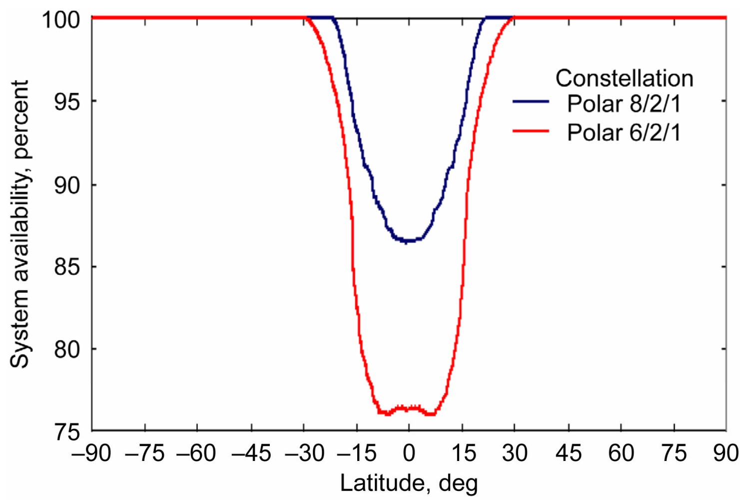

Figure B.8.1.—PDoP 15-min dynamic system availability performance for no terrain, two-way operation.

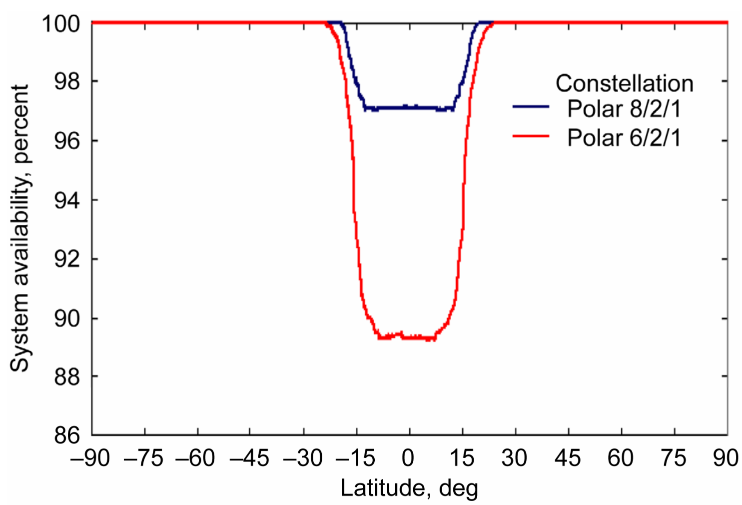

Figure B.9.1.—PDoP 1-hr dynamic system availability performance for no terrain, two-way operation.

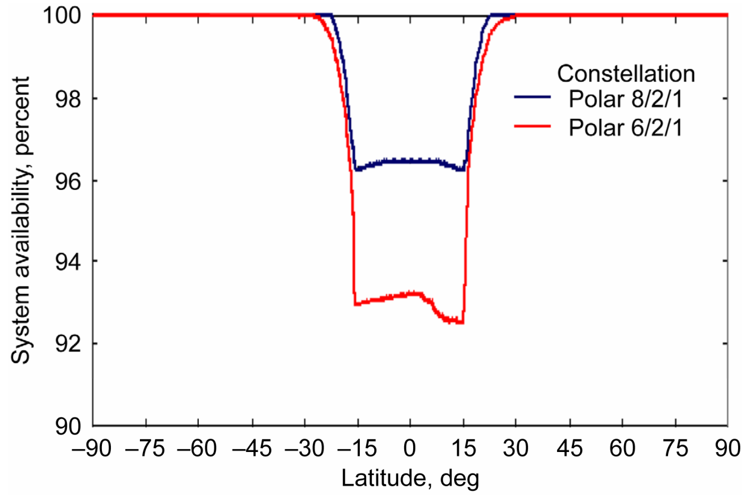

Figure B.10.1.—HDoP kinematic system availability performance for good terrain, two-way operation.

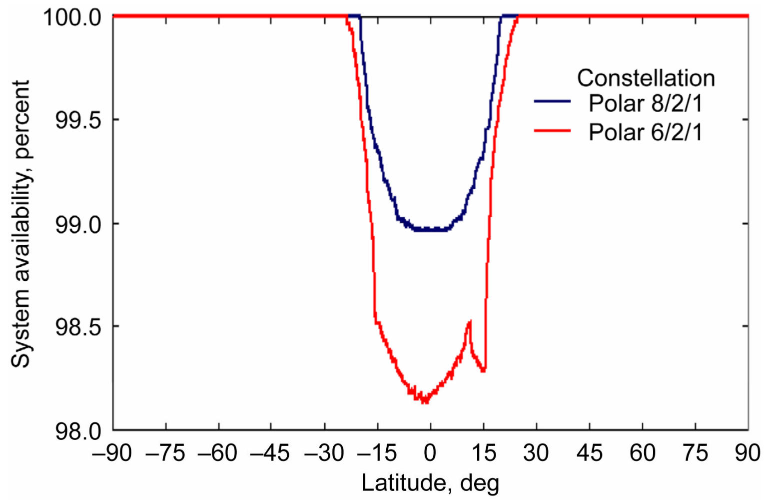

Figure B.11.1.—HDoP 15-min dynamic system availability performance for good terrain, two-way operation.

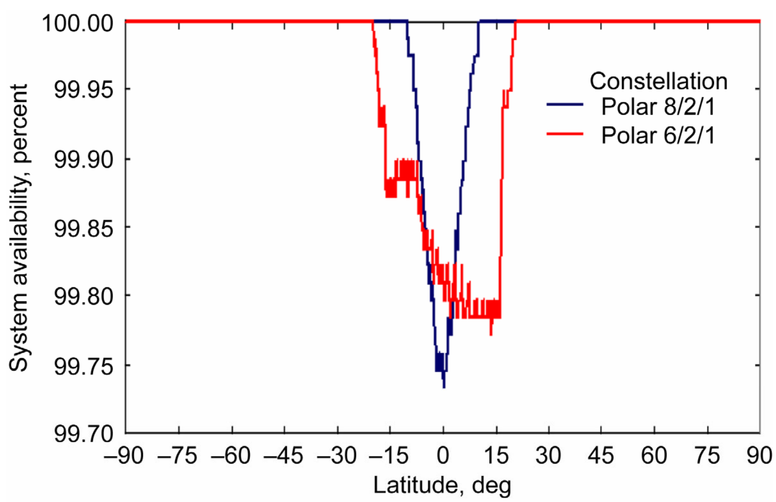

Figure B.12.1.—HDoP 1-hr dynamic system availability performance for good terrain, two-way operation.

Appendix C—Elevation Study

All figures in appendix C are described as follows: the solid blue line connects the system availability performance from each of the minimum elevation angles versus the system availability for the polar 8/2/1 constellation. The red line serves the same purpose for the polar 6/2/1 constellation.

C.1 GDoP kinematic results

Figure C.1.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with kinematic measurements.

C.2 GDoP dynamic 15-min results

Figure C.2.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 15-min dynamic measurements.

C.3 GDoP dynamic 1-hr results

Figure C.3.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 1-hr dynamic measurements.

C.4 HTDoP kinematic results

Figure C.4.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with kinematic measurements.

C.5 HTDoP dynamic 15-min results

Figure C.5.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 15-min dynamic measurements.

C.6 HTDoP dynamic 1-hr results

Figure C.6.1 illustrates the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 1-hr dynamic measurements.

C.7 PDoP kinematic results

Figure C.7.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with kinematic measurements.

C.8 PDoP dynamic 15-min results

Figure C.8.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 15-min dynamic measurements.

C.9 PDoP dynamic 1-hr results

Figure C.9.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 1-hr dynamic measurements.

C.10 HDoP kinematic results

Figure C.10.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with kinematic measurements.

C.11 HDoP dynamic 15-min results

Figure C.11.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 15-min dynamic measurements.

C.12 HDoP dynamic 1-hr results

Figure C.12.1 illustrates the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 1-hr dynamic measurements.

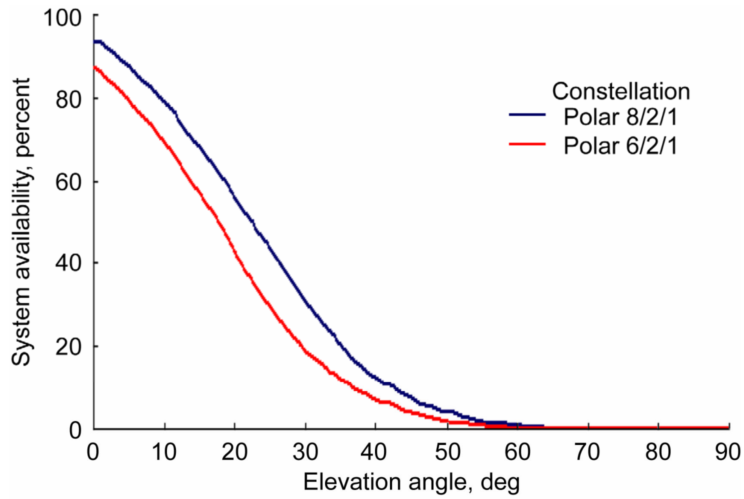

Figure C.1.1.—GDoP kinematic system availability performance for no terrain, one-way operation.

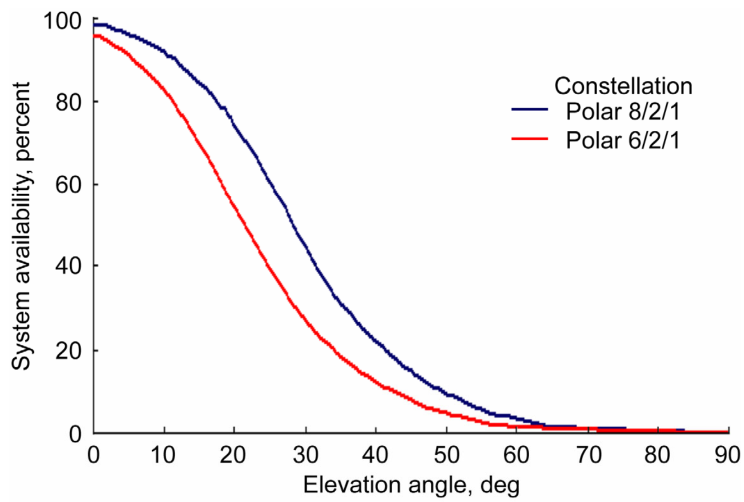

Figure C.2.1.—GDoP 15-min dynamic system availability performance for no terrain, one-way operation.

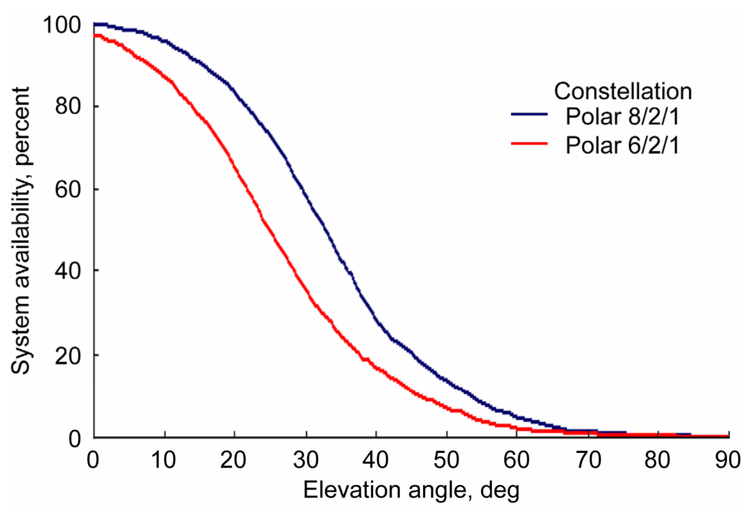

Figure C.3.1.—GDoP 1-hr dynamic system availability performance for no terrain, one-way operation.

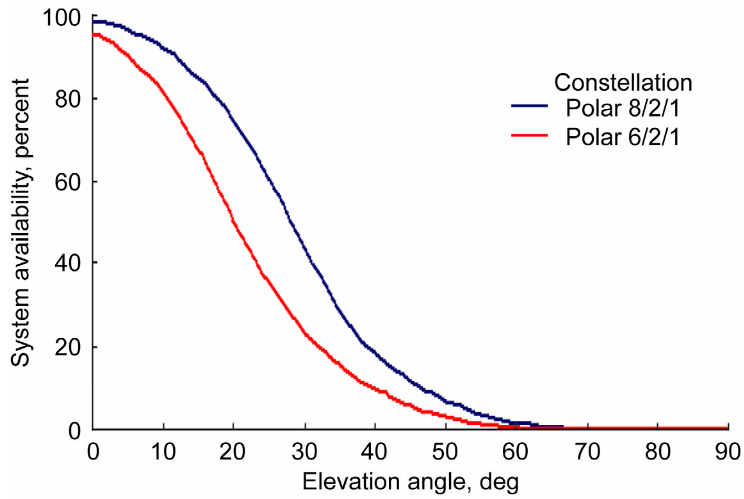

Figure C.4.1.—HTDoP kinematic system availability performance for good terrain, one-way operation.

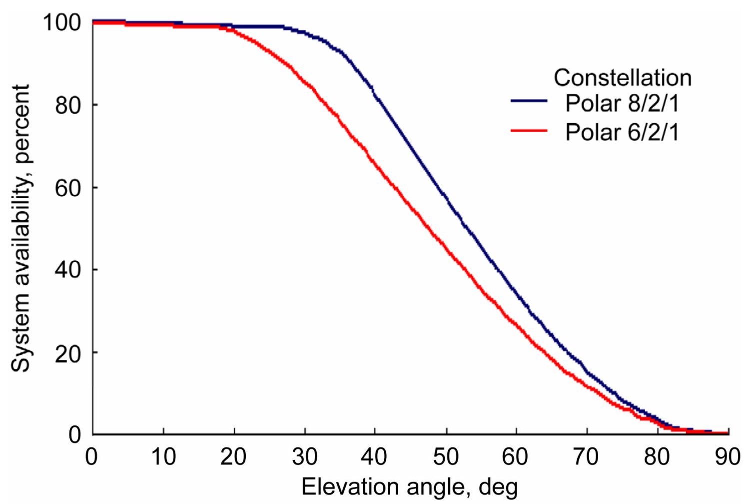

Figure C.5.1.—HTDoP 15-min dynamic system availability performance for good terrain, one-way operation.

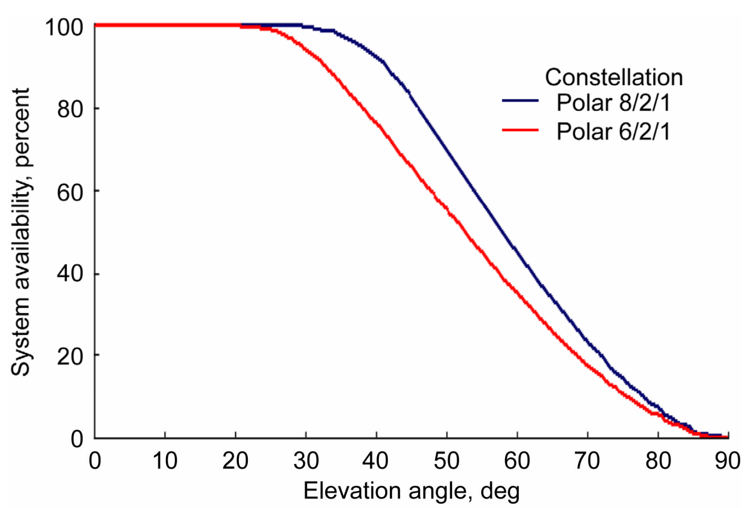

Figure C.6.1.—HTDoP 1-hr dynamic system availability performance for good terrain, one-way operation.

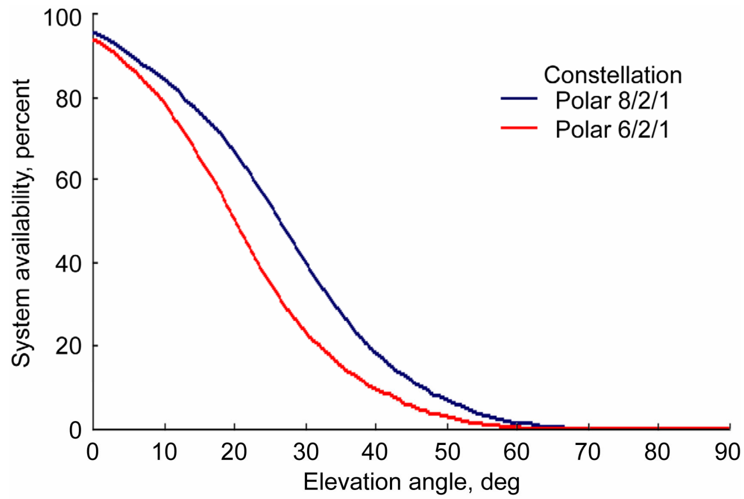

Figure C.7.1.—PDoP kinematic system availability performance for no terrain, two-way operation.

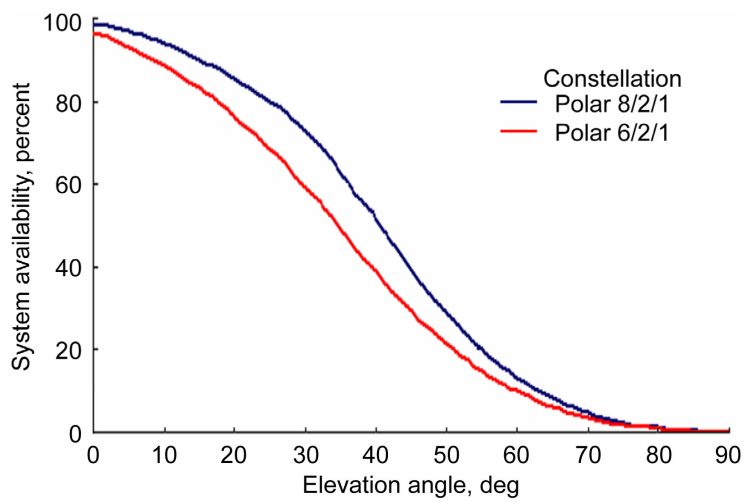

Figure C.8.1.—PDoP 15-min dynamic system availability performance for no terrain, two-way operation.

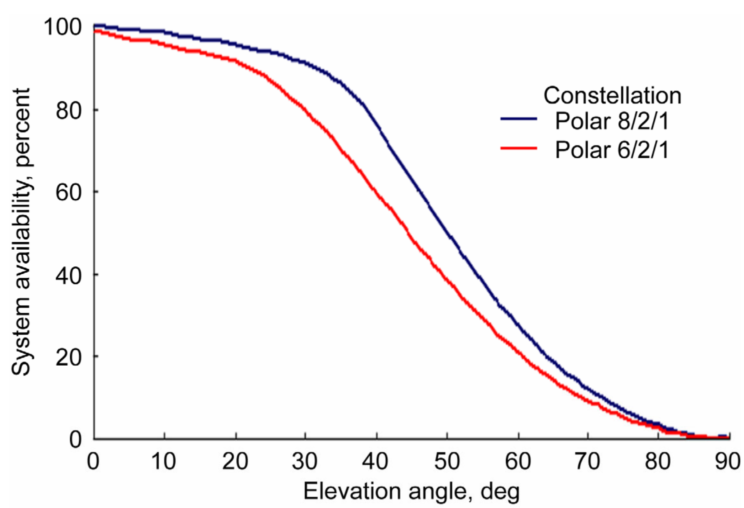

Figure C.9.1.—PDoP 1-hr dynamic system availability performance for no terrain, two-way operation.

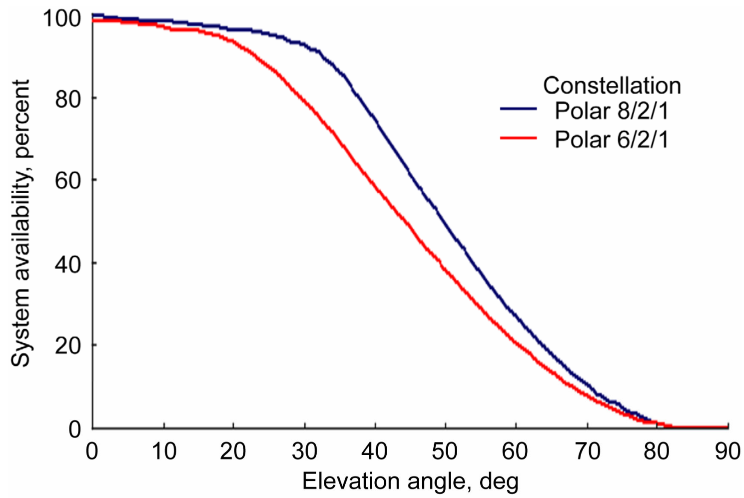

Figure C.10.1.—HDoP kinematic system availability performance for good terrain, two-way operation.

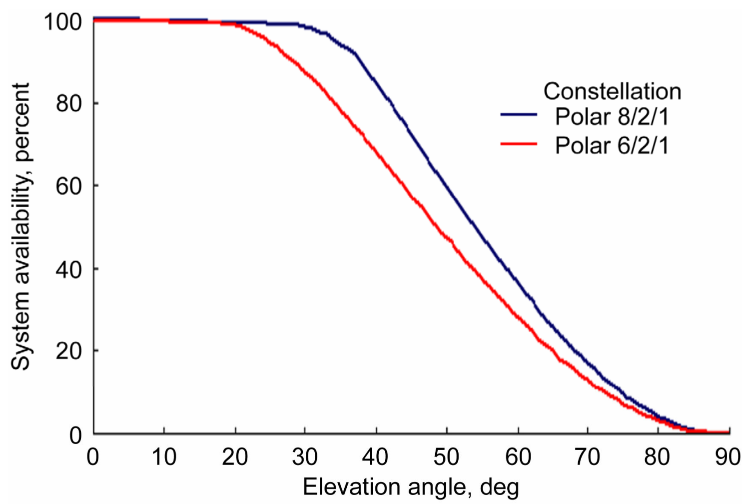

Figure C.11.1.—HDoP 15-min dynamic system availability performance for good terrain, two-way operation.

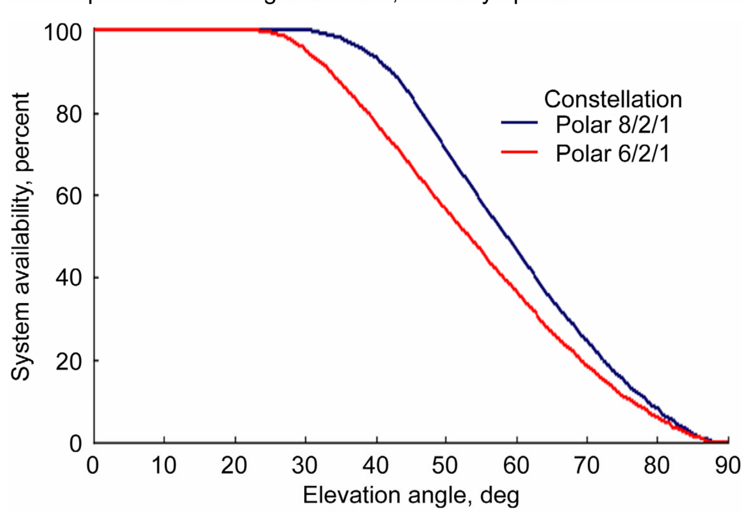

Figure C.12.1.—HDoP 1-hr dynamic system availability performance for good terrain, two-way operation.

Appendix D—Modified Failure Mode Study

The figures in appendix D show the system availability results for the two constellations, illustrating the three variations of each of the constellations. The mode variations are nonfailure, modified failure, and failure. The first row of subplots pertain to the polar 8/2/1 constellation, and the second row illustrates the performance of the polar 6/2/1 constellation. The first column pertains to the nonfailure mode of each constellation, and the second and third columns represent the modified failure mode and failure mode, respectively. The system availability results are superimposed on a Mercator projection of the lunar surface.

D.1 GDoP kinematic results

Figures D.1.1 to D.1.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with kinematic measurements for the three user minimum elevation angles.

D.2 GDoP dynamic 15-min results

Figures D.2.1 to D.2.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 15-min dynamic measurements for the three user minimum elevation angles.

D.3 GDoP dynamic 1-hr results

Figures D.3.1 to D.3.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode without terrain information and with 1-hr dynamic measurements for the three user minimum elevation angles.

D.4 HTDoP kinematic results

Figures D.4.1 to D.4.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with kinematic measurements for the three user minimum elevation angles.

D.5 HTDoP dynamic 15-min results

Figures D.5.1 to D.5.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 15-min dynamic measurements for the three user minimum elevation angle.

D.6 HTDoP dynamic 1-hr results

Figures D.6.1 to D.6.3 illustrate the performance of the two constellations when the surface users are operating in the one-way mode with terrain information and with 1-hr dynamic measurements for the three user minimum elevation angles.

D.7 PDoP kinematic results

Figures D.7.1 to D.7.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with kinematic measurements for the three user minimum elevation angles.

D.8 PDoP dynamic 15-min results

Figures D.8.1 to D.8.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 15-min dynamic measurements for the three user minimum elevation angles.

D.9 PDoP dynamic 1-hr results

Figures D.9.1 to D.9.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode without terrain information and with 1-hr dynamic measurements for the three user minimum elevation angles.

D.10 HDoP kinematic results

Figures D.10.1 to D.10.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with kinematic measurements for the three user minimum elevation angles.

D.11 HDoP dynamic 15-min results

Figures D.11.1 to D.11.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 15-min dynamic measurements for the three user minimum elevation angles.

D.12 HDoP dynamic 1-hr results

Figures D.12.1 to D.12.3 illustrate the performance of the two constellations when the surface users are operating in the two-way mode with terrain information and with 1-hr dynamic measurements for the three user minimum elevation angles.

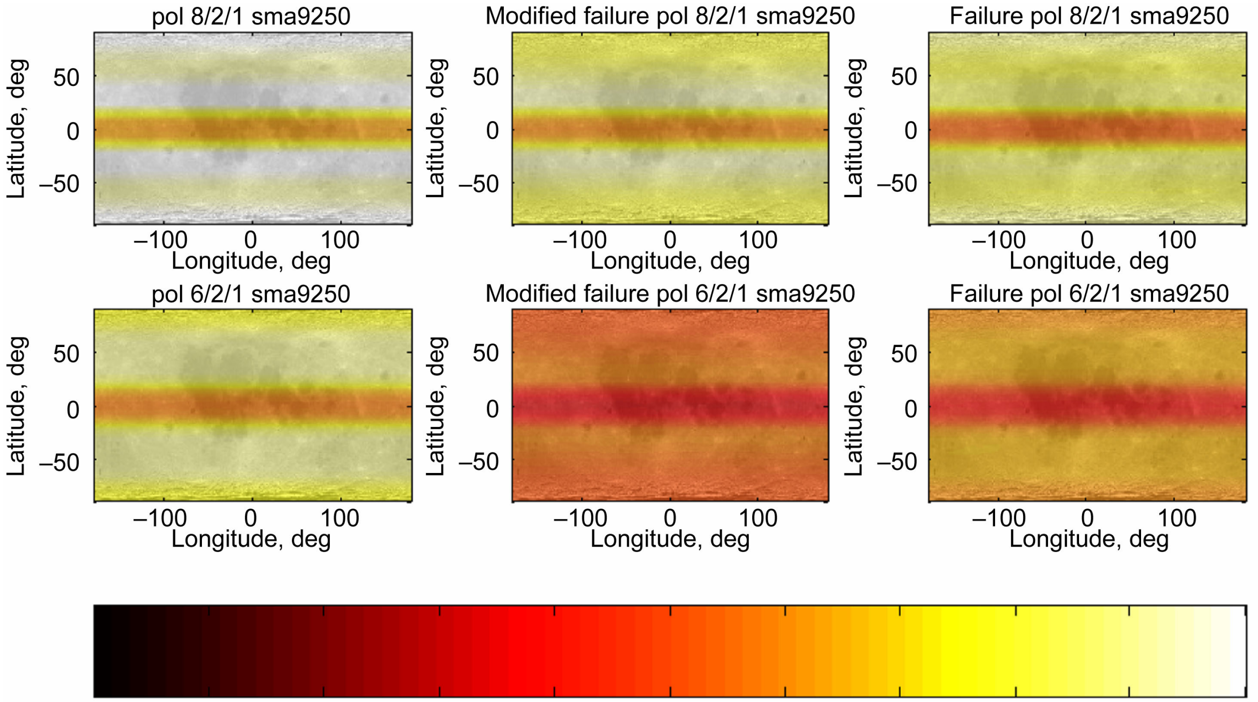

Figure D.1.1.—GDoP kinematic system availability performance for 5° elevation angle with no terrain, one-way operation.

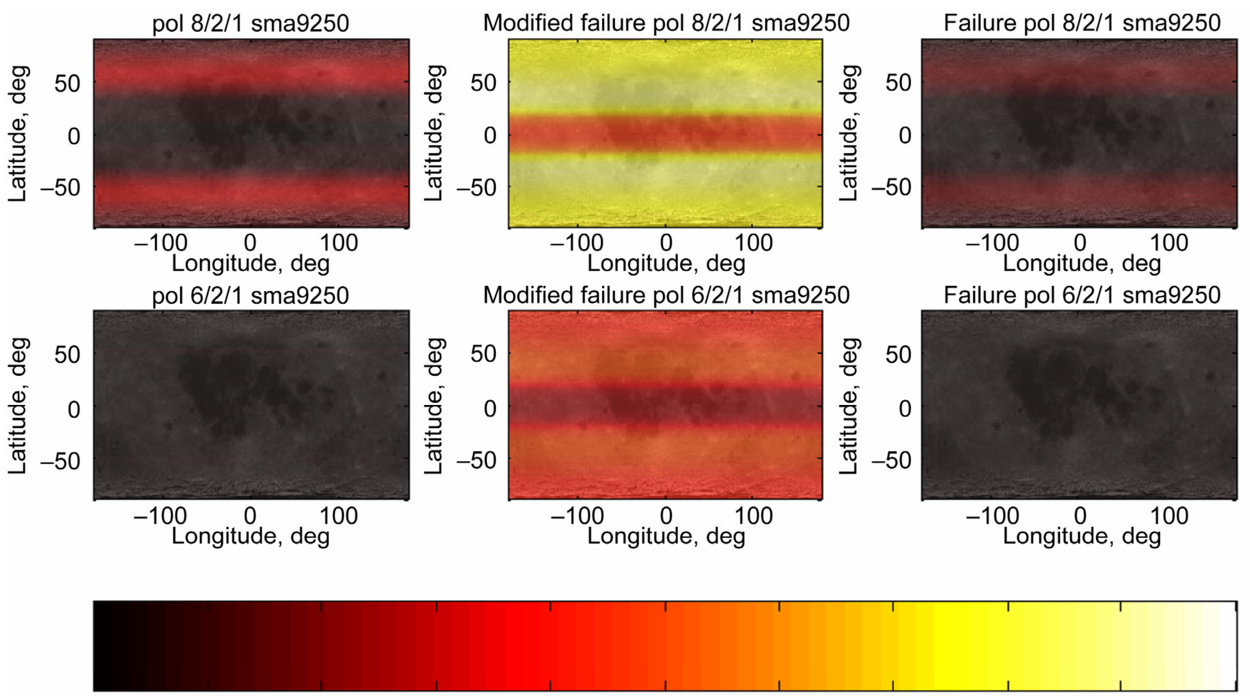

Figure D.1.2.—GDoP kinematic system availability performance for 10° elevation angle with no terrain, one-way operation.

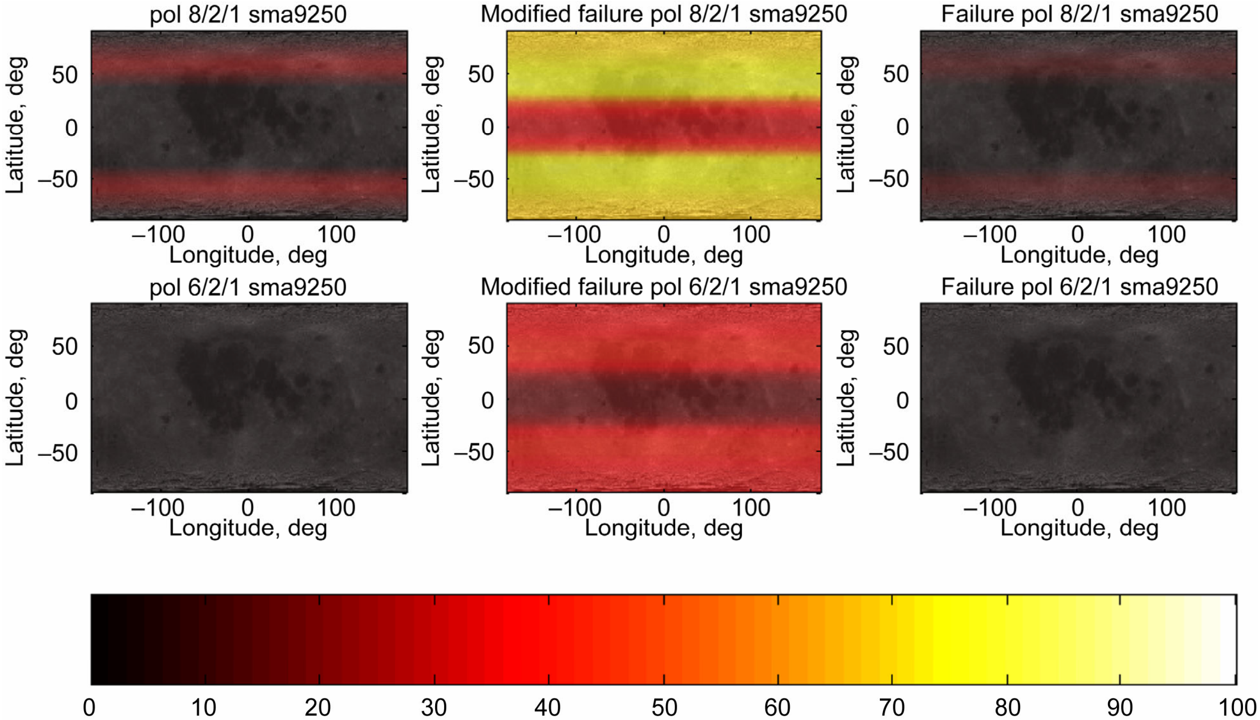

Figure D.1.3.—GDoP kinematic system availability performance for 15° elevation angle with no terrain, one-way operation.

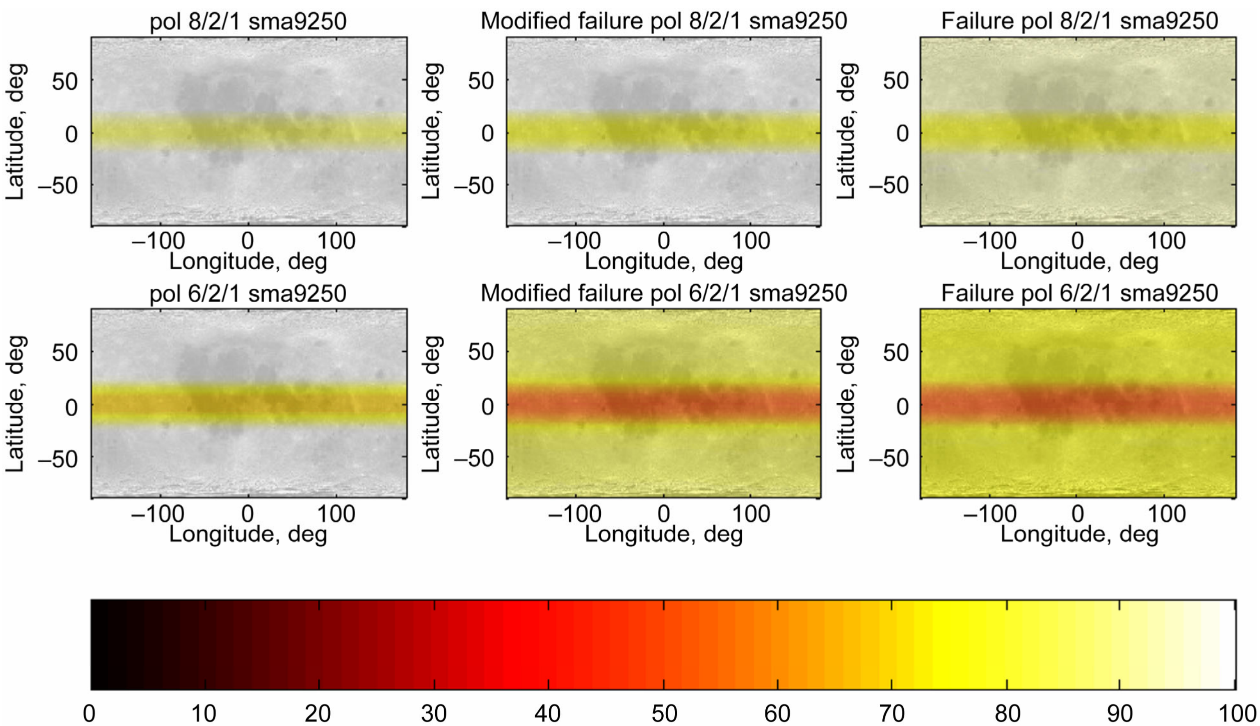

Figure D.2.1.—GDoP 15-min dynamic system availability performance for 5° elevation angle with no terrain, one-way operation.

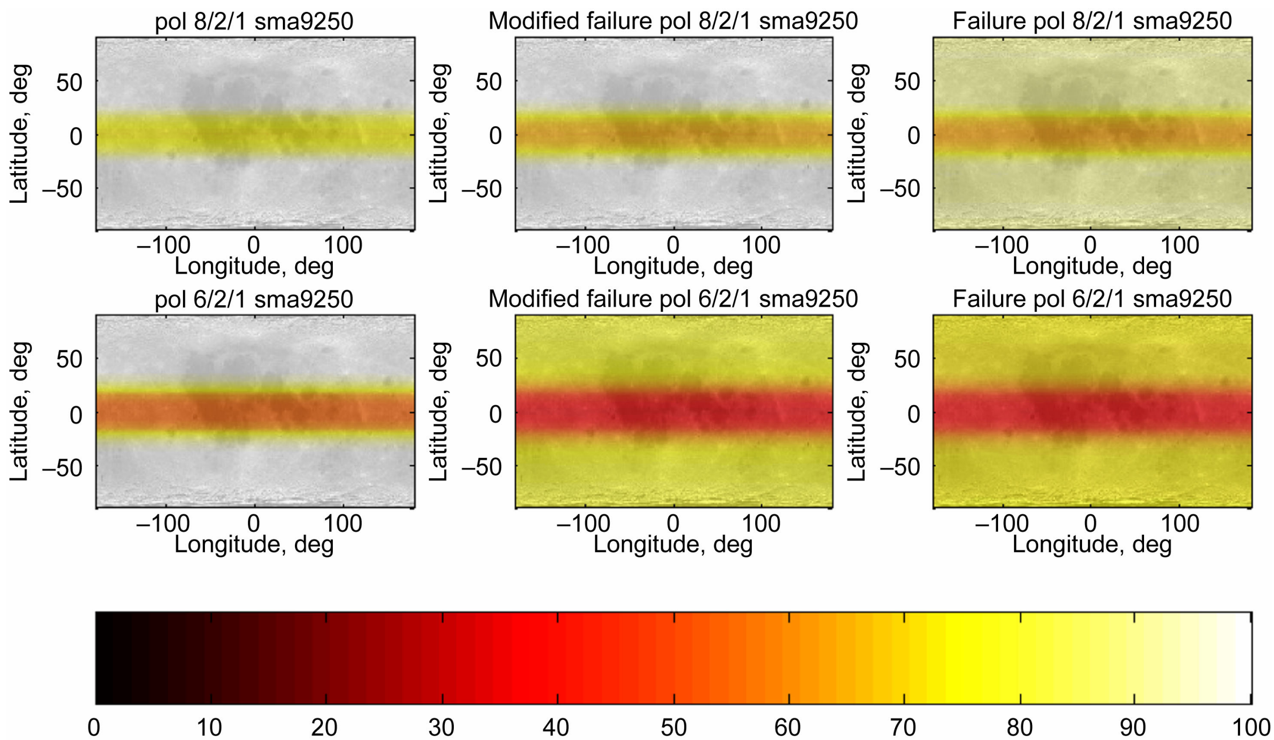

Figure D.2.2.—GDoP 15-min dynamic system availability performance for 10° elevation angle with no terrain, one-way operation.

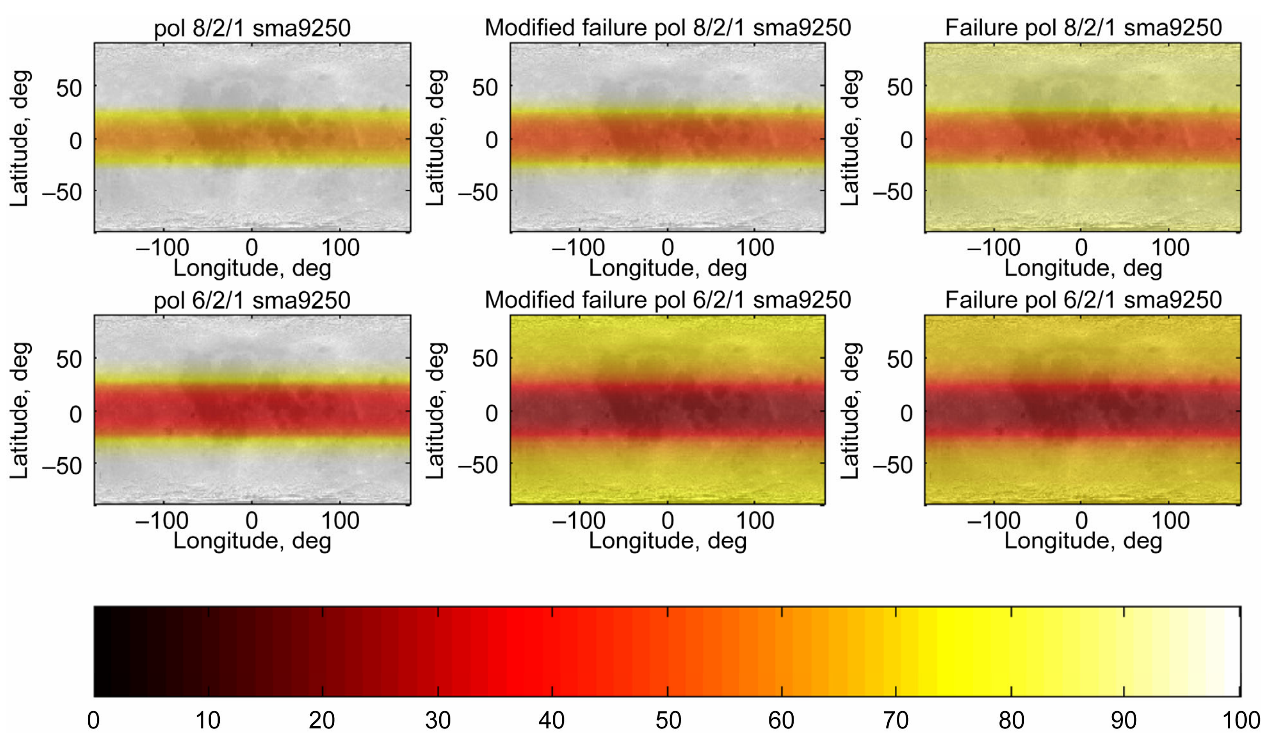

Figure D.2.3.—GDoP 15-min dynamic system availability performance for 15° elevation angle with no terrain, one-way operation.

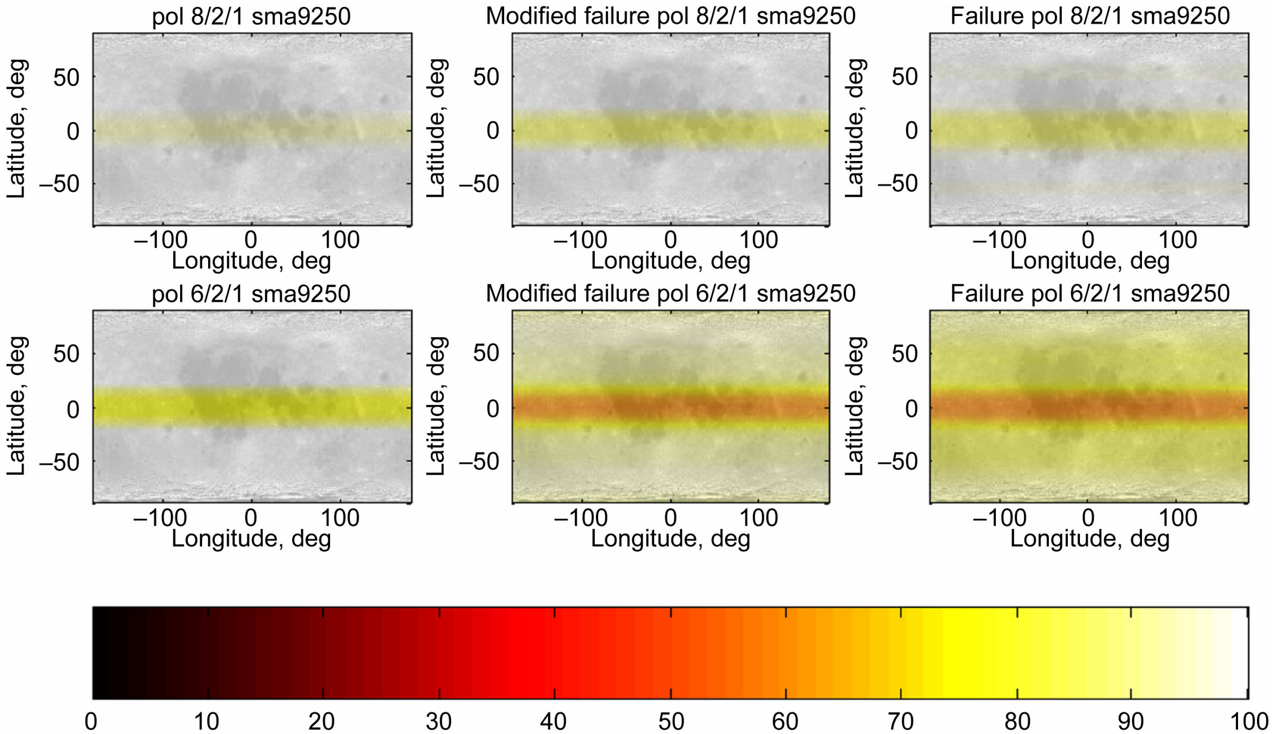

Figure D.3.1.—GDoP 1-hr dynamic system availability performance for 5° elevation angle with no terrain, one-way operation.

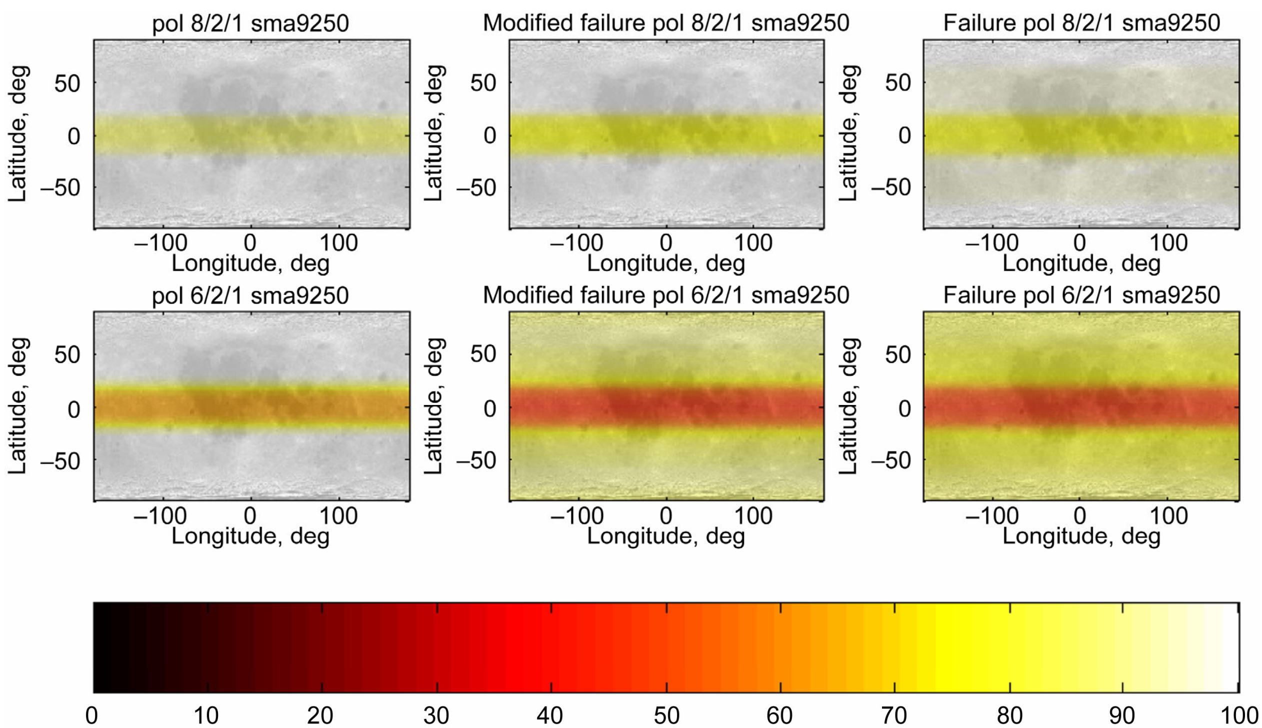

Figure D.3.2.—GDoP 1-hr dynamic system availability performance for 10° elevation angle with no terrain, one-way operation.

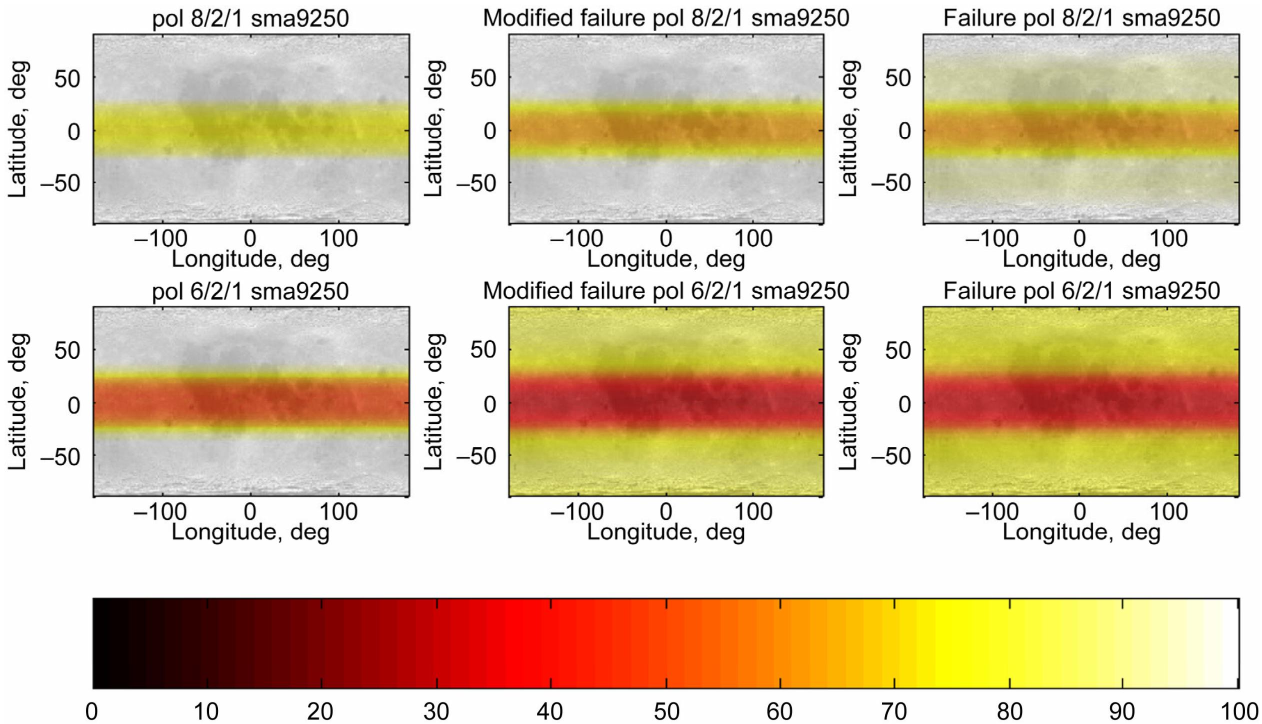

Figure D.3.3.—GDoP 1-hr dynamic system availability performance for 15° elevation angle with no terrain, one-way operation.

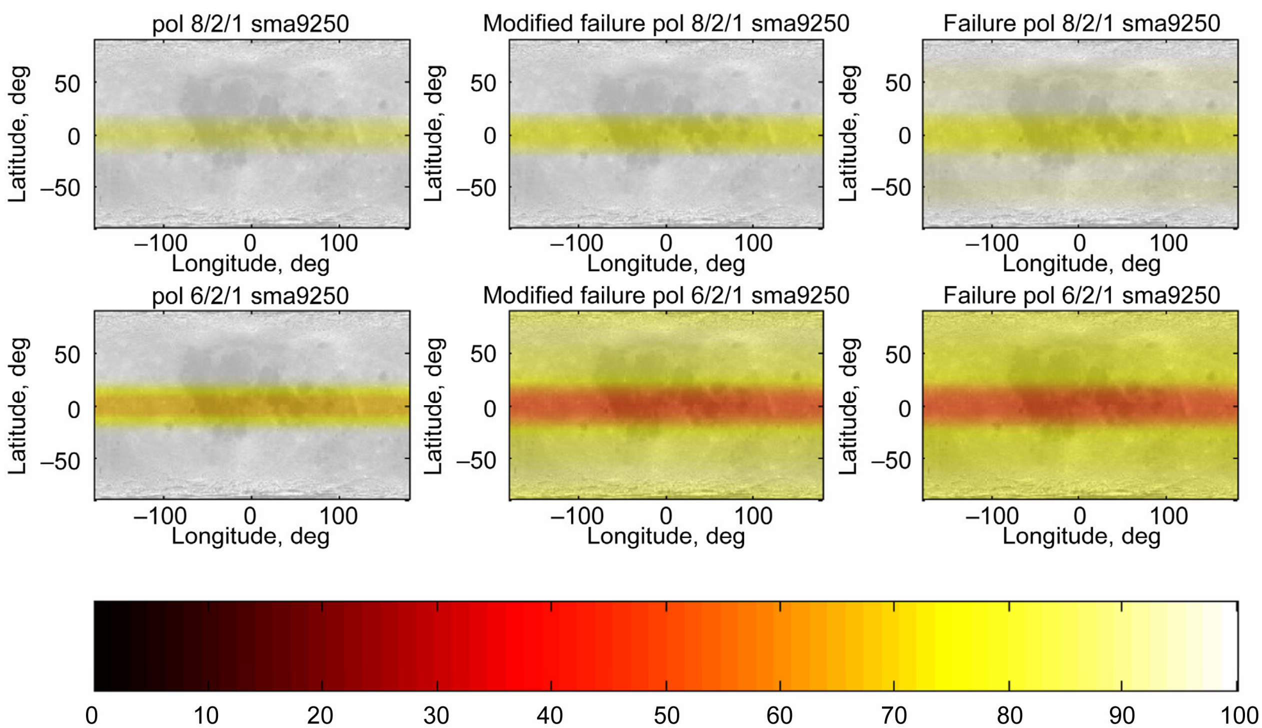

Figure D.4.1.—HTDoP kinematic system availability performance for 5° elevation angle with good terrain, one-way operation.

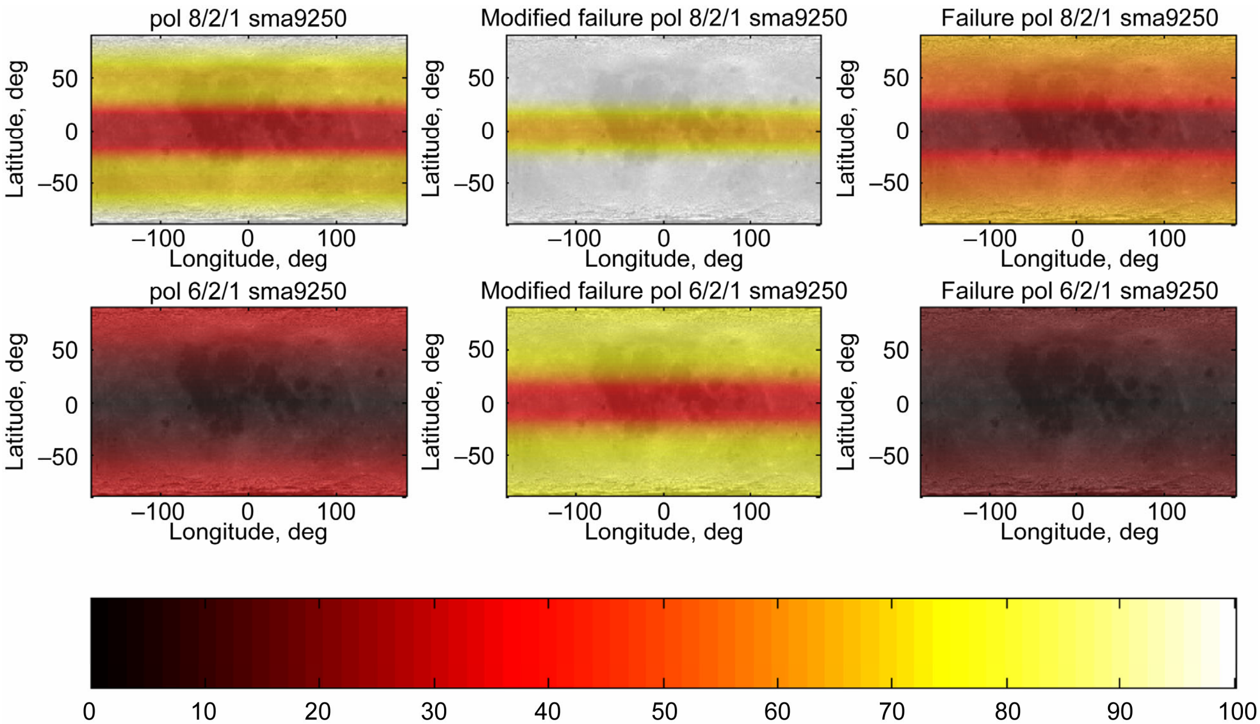

Figure D.4.2.—HTDoP kinematic system availability performance for 10° elevation angle with good terrain, one-way operation.

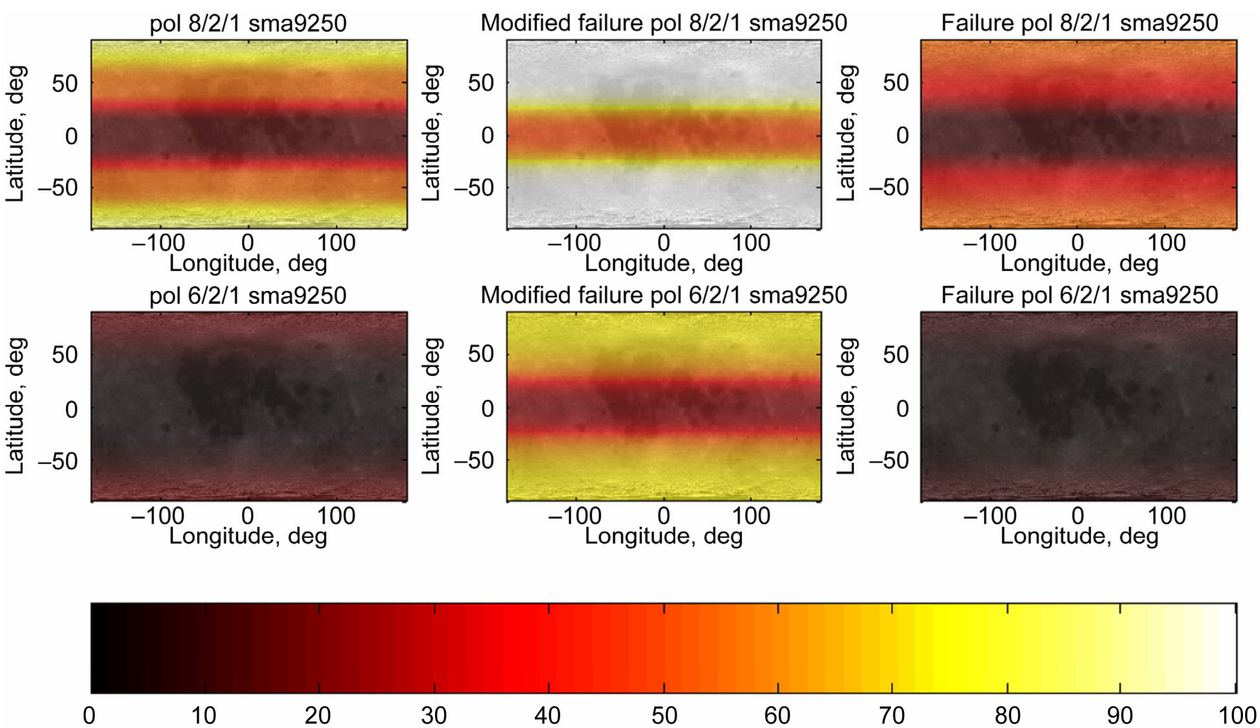

Figure D.4.3.—HTDoP kinematic system availability performance for 15° elevation angle with good terrain, one-way operation.

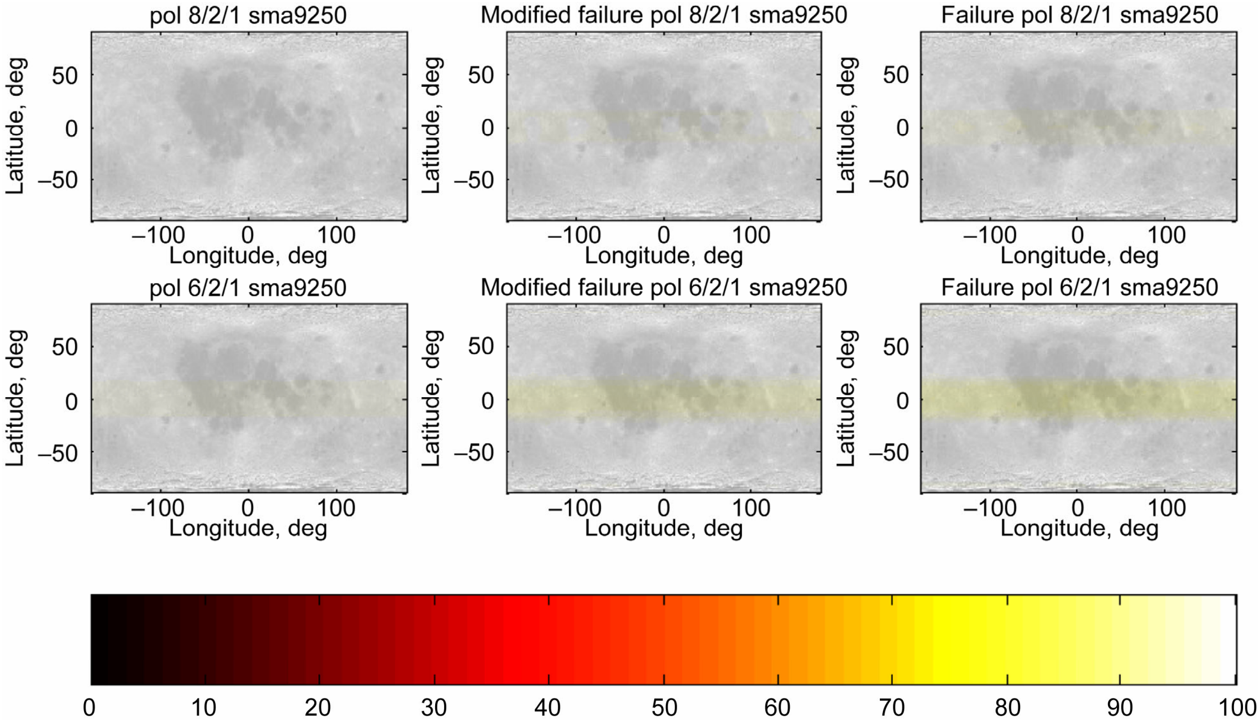

Figure D.5.1.—HTDoP 15-min dynamic system availability performance for 5° elevation angle with good terrain, one-way operation.

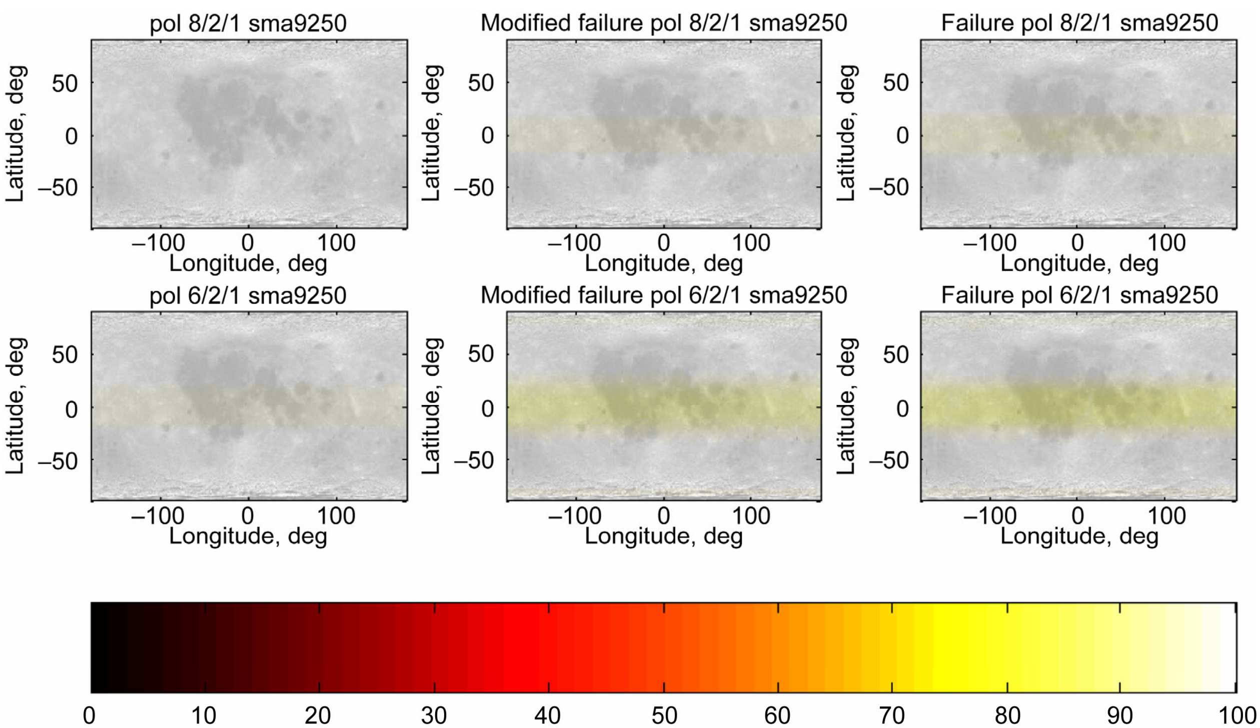

Figure D.5.2.—HTDoP 15-min dynamic system availability performance for 10° elevation angle with good terrain, one-way operation.

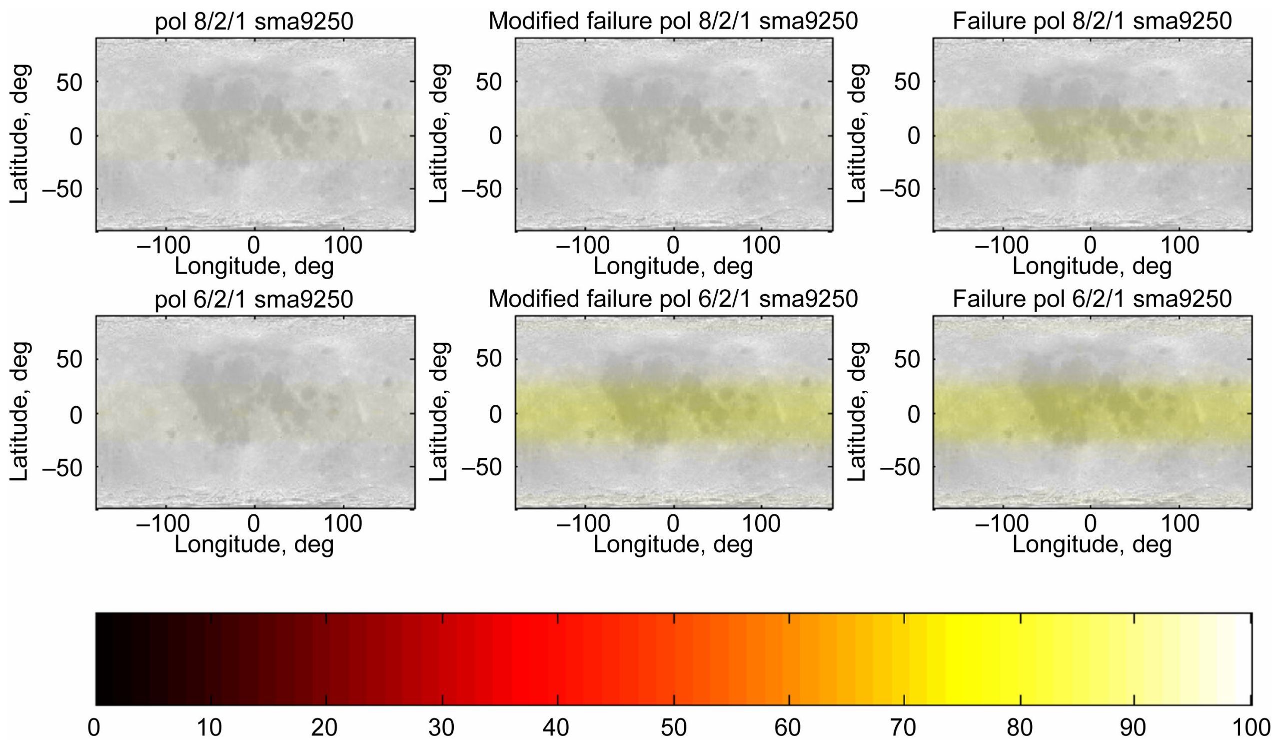

Figure D.5.3.—HTDoP 15-min dynamic system availability performance for 15° elevation angle with good terrain, one-way operation.

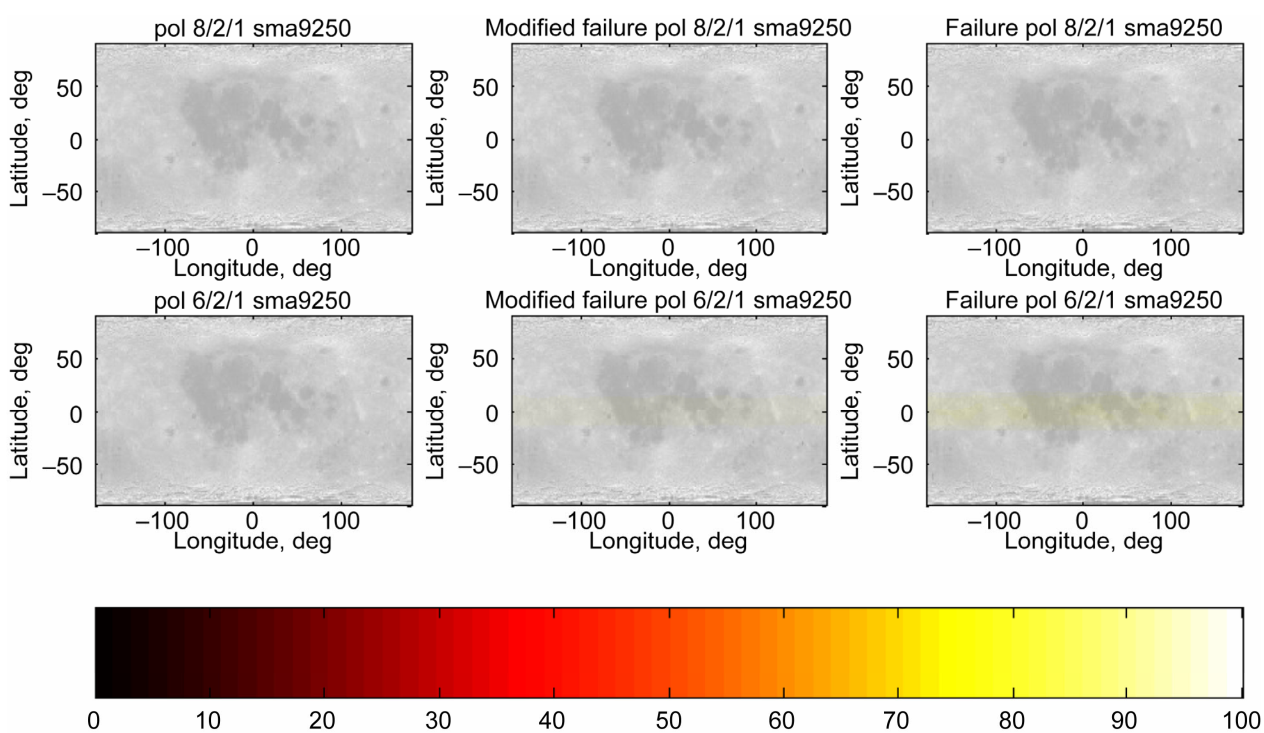

Figure D.6.1.—HTDoP 1-hr dynamic system availability performance for 5° elevation angle with good terrain, one-way operation.

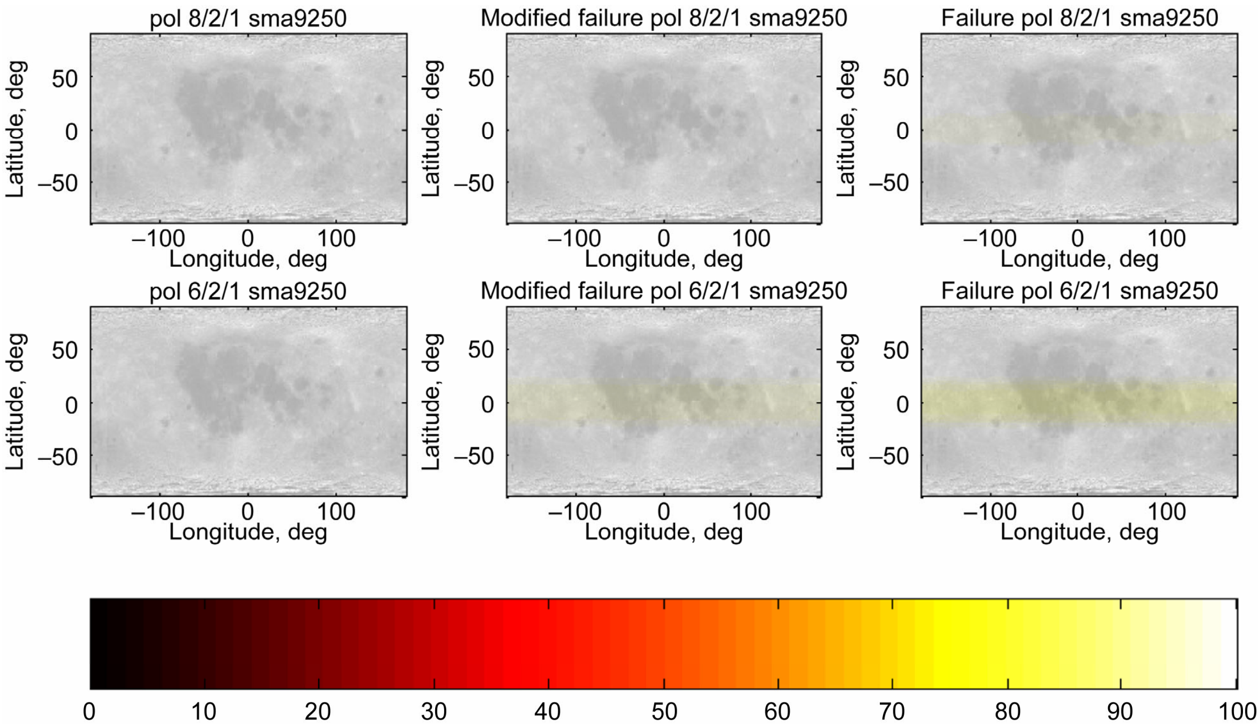

Figure D.6.2.—HTDoP 1-hr dynamic system availability performance for 10° elevation angle with good terrain, one-way operation.

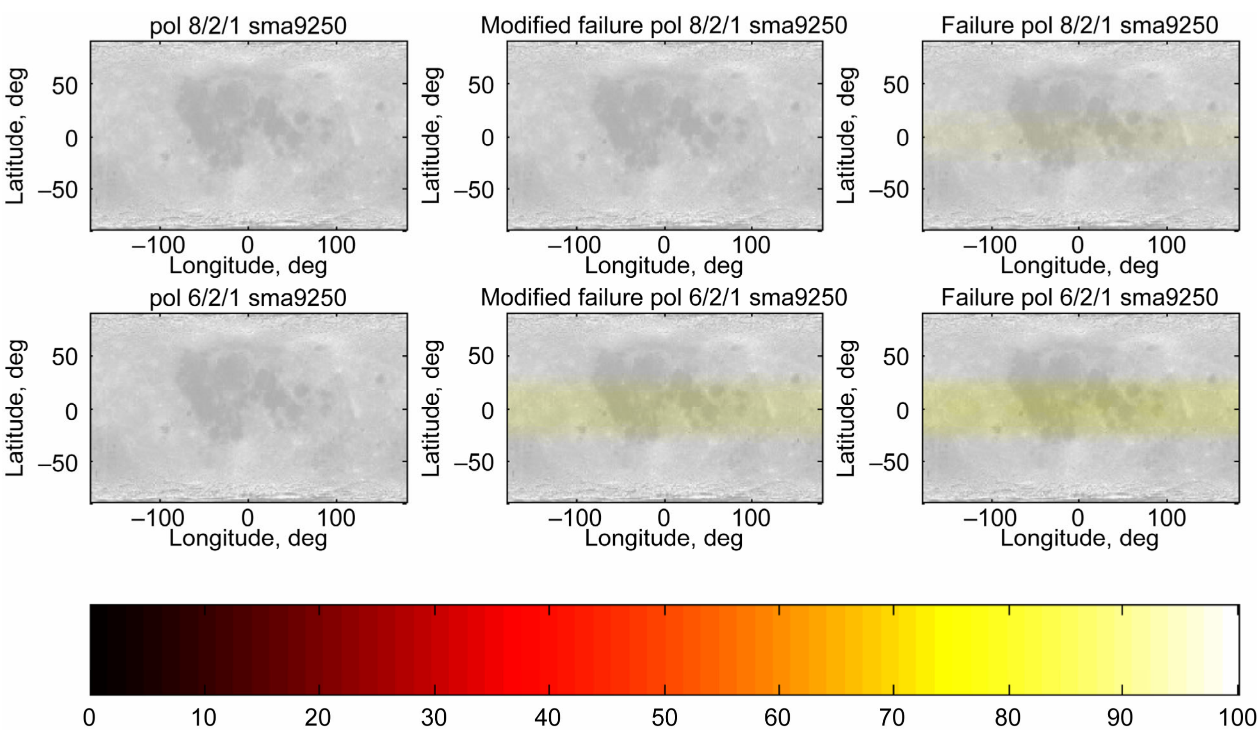

Figure D.6.3.—HTDoP 1-hr dynamic system availability performance for 15° elevation angle with good terrain, one-way operation.

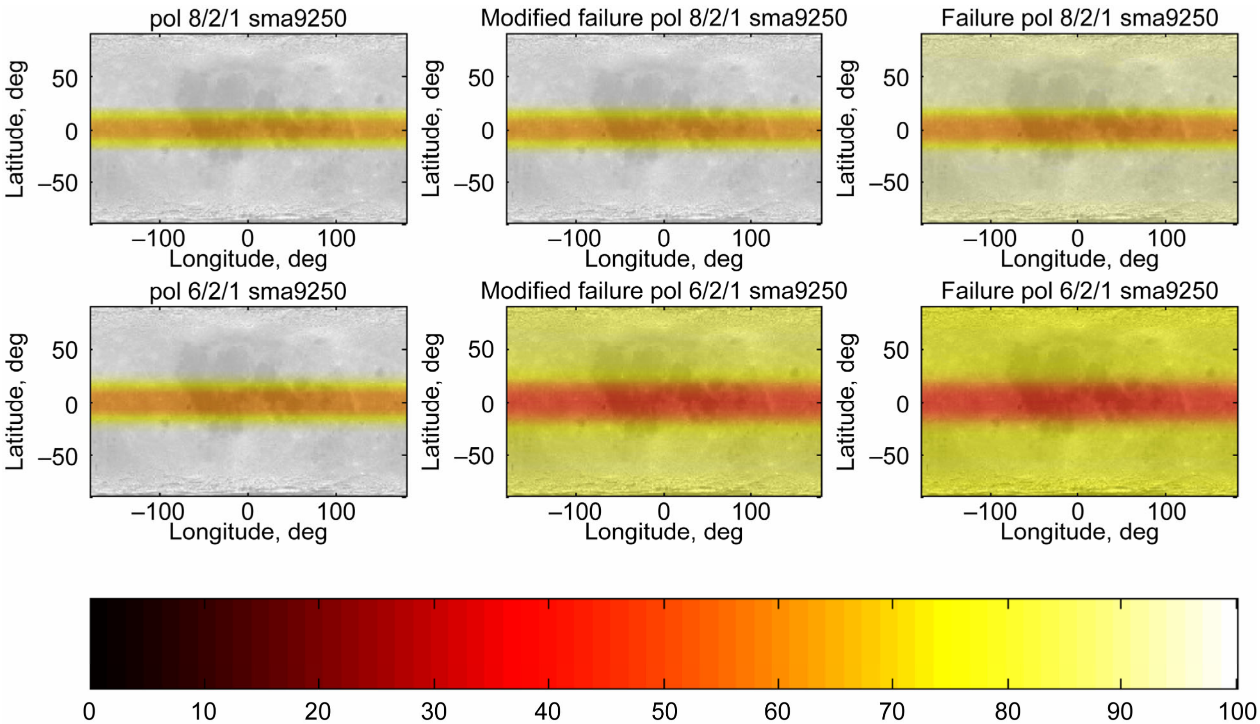

Figure D.7.1.—PDoP kinematic system availability performance for 5° elevation angle with no terrain, two-way operation.

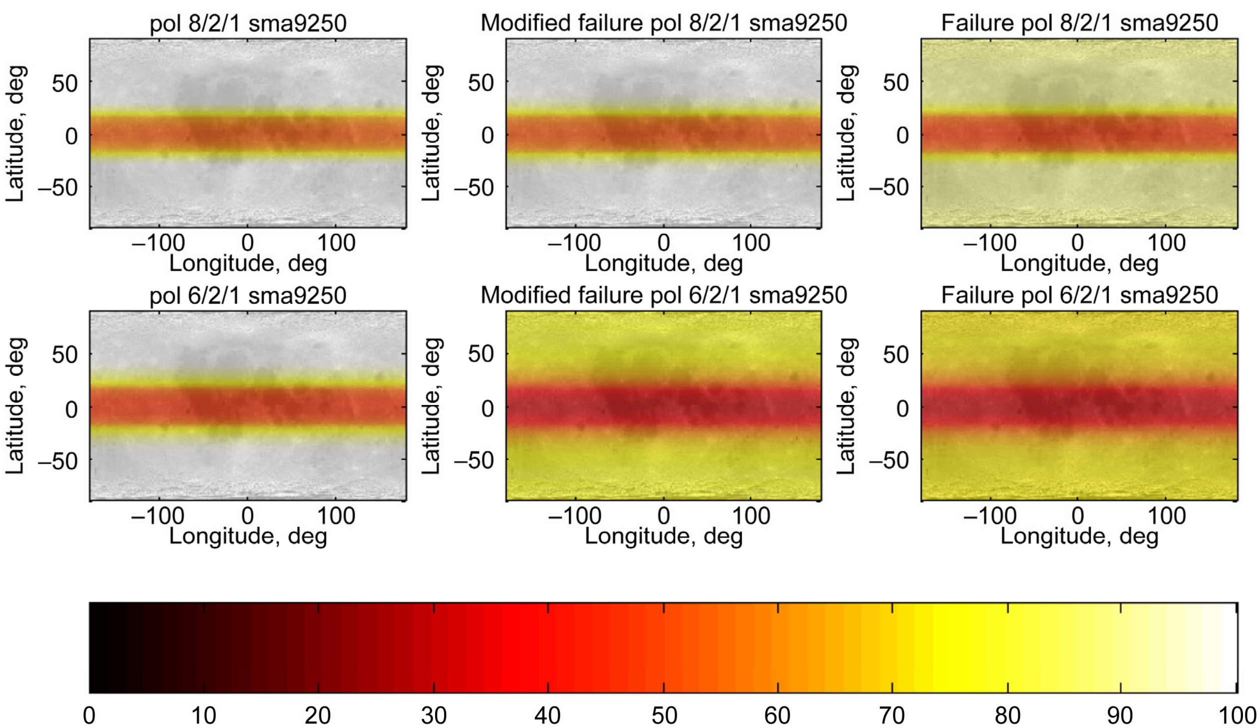

Figure D.7.2.—PDoP kinematic system availability performance for 10° elevation angle with no terrain, two-way operation.

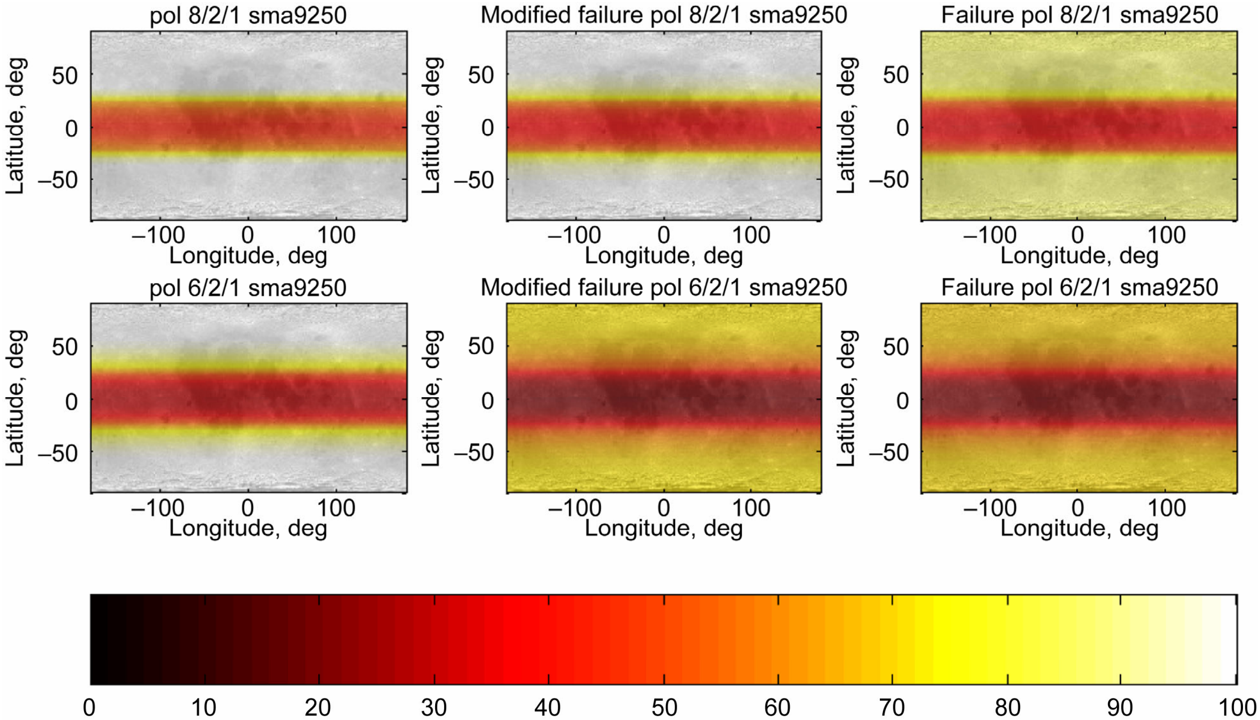

Figure D.7.3.—PDoP kinematic system availability performance for 15° elevation angle with no terrain, two-way operation.

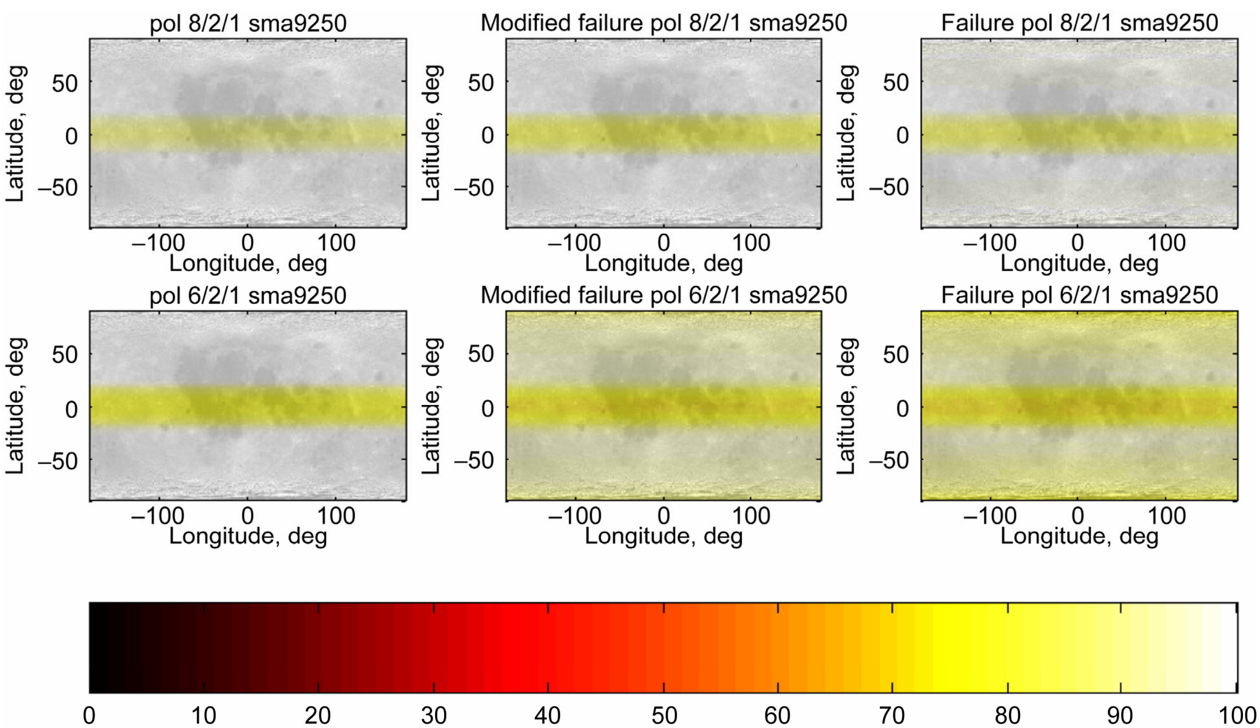

Figure D.8.1.—PDoP 15-min dynamic system availability performance for 5° elevation angle with no terrain, two-way operation.

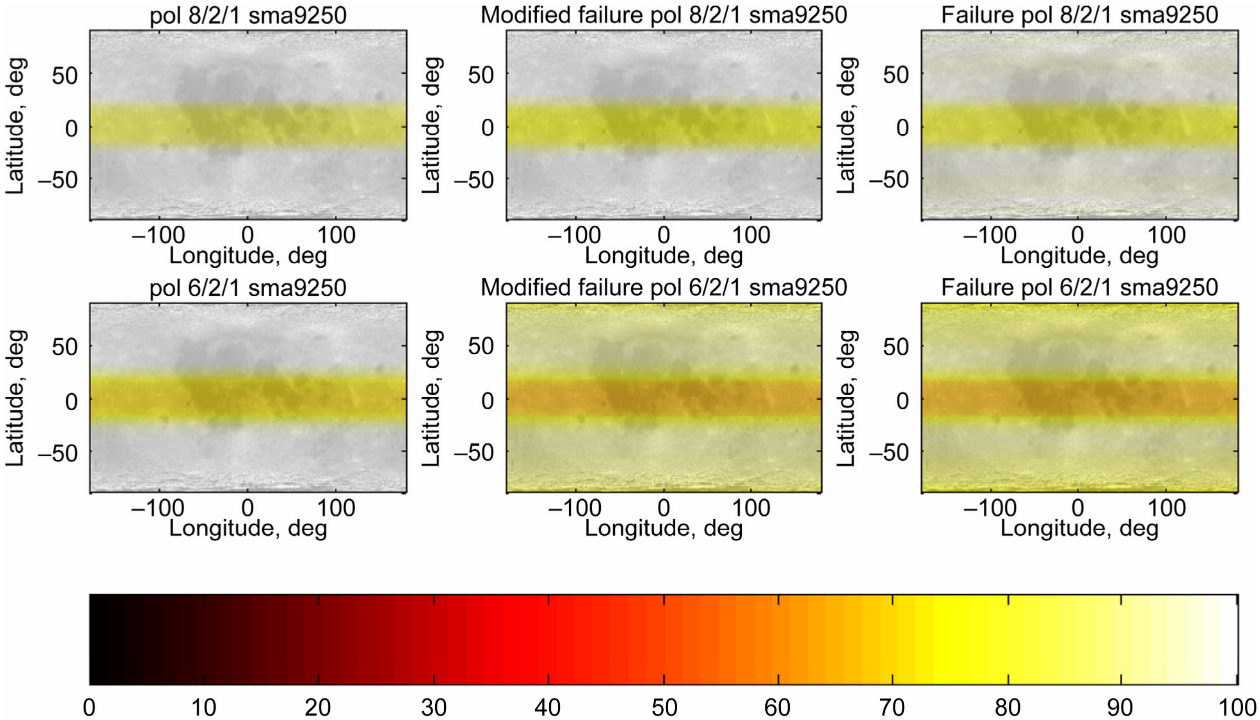

Figure D.8.2.—PDoP 15-min dynamic system availability performance for 10° elevation angle with no terrain, two-way operation.

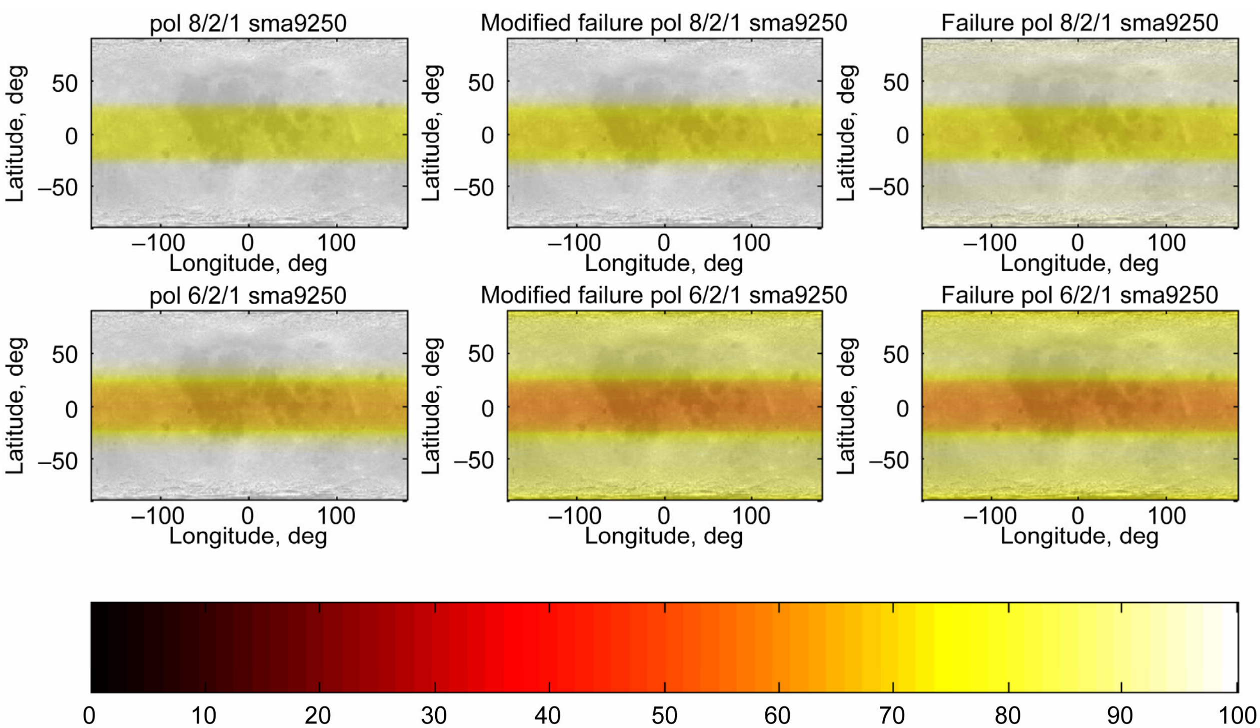

Figure D.8.3.—PDoP 15-min dynamic system availability performance for 15° elevation angle with no terrain, two-way operation.

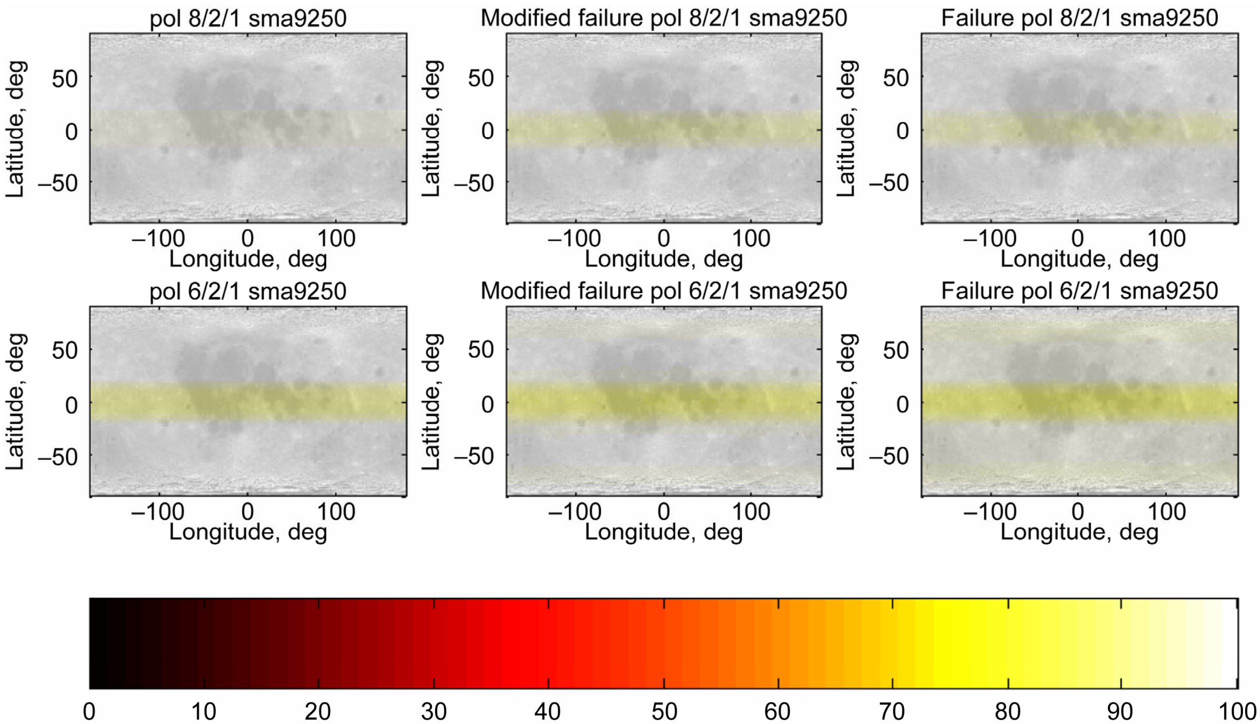

Figure D.9.1.—PDoP 1-hr dynamic system availability performance for 5° elevation angle with no terrain, two-way operation.

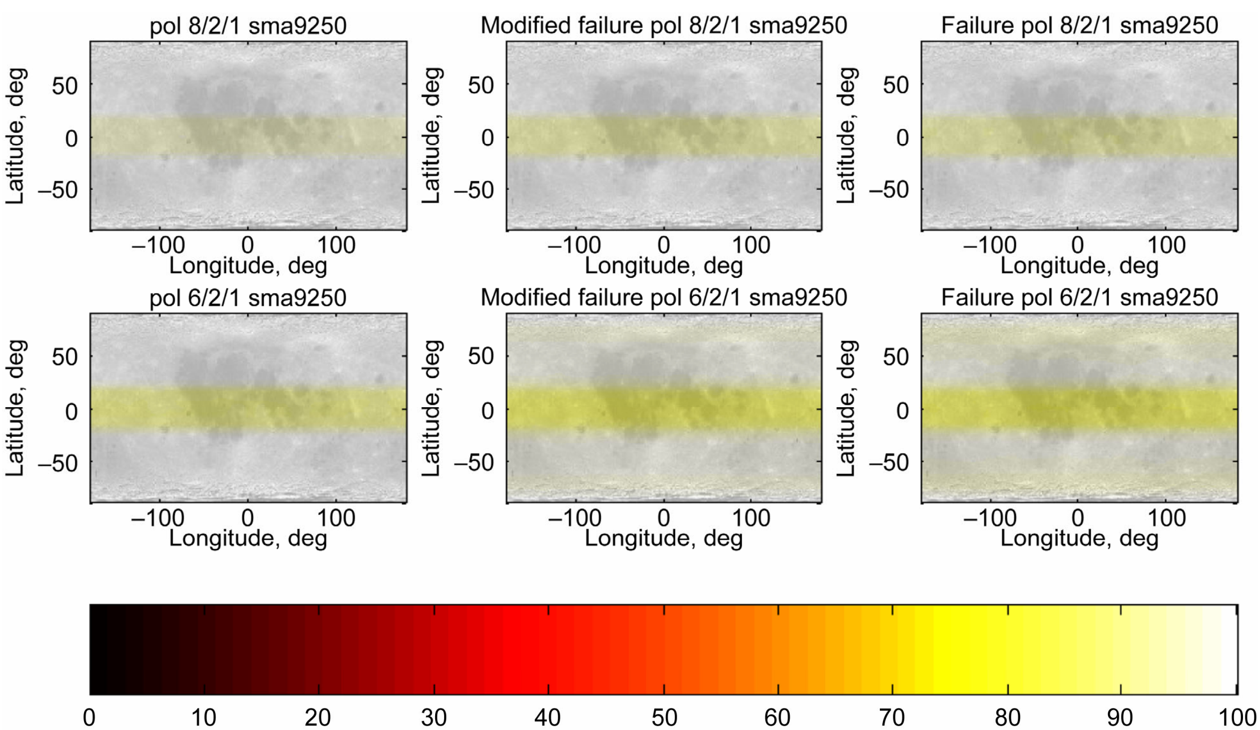

Figure D.9.2.—PDoP 1-hr dynamic system availability performance for 10° elevation angle with no terrain, two-way operation.

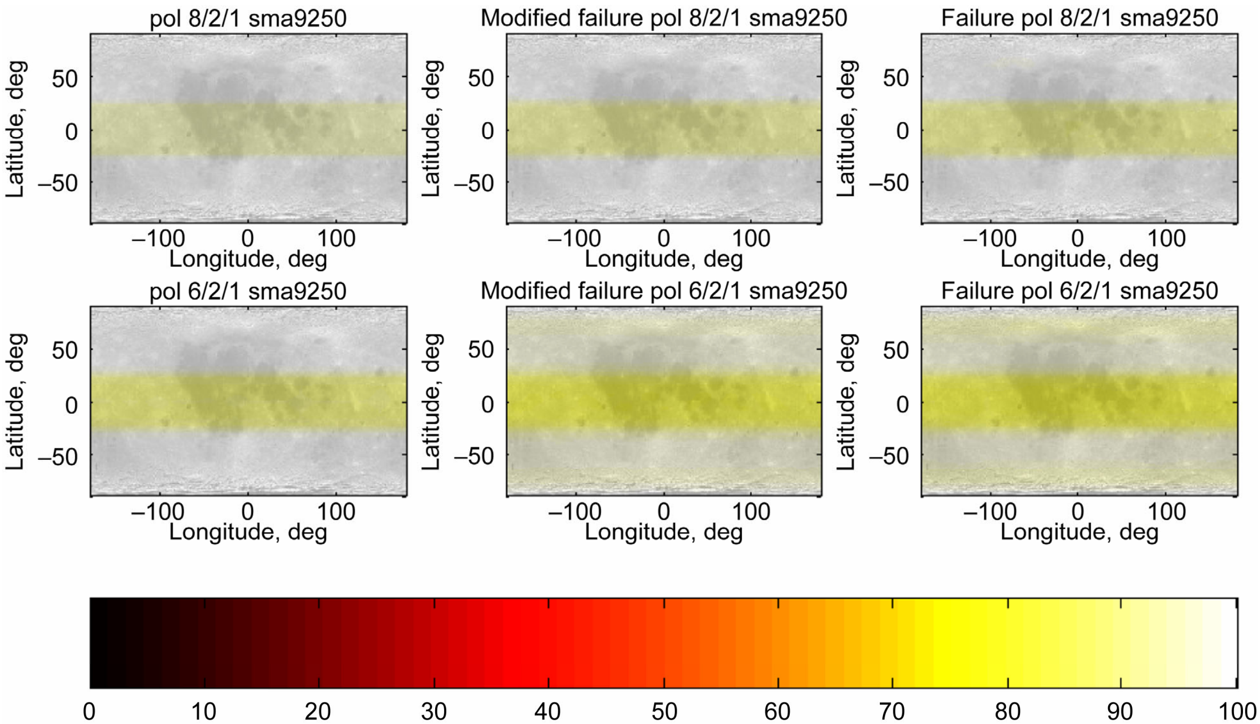

Figure D.9.3.—PDoP 1-hr dynamic system availability performance for 15° elevation angle with no terrain, two-way operation.

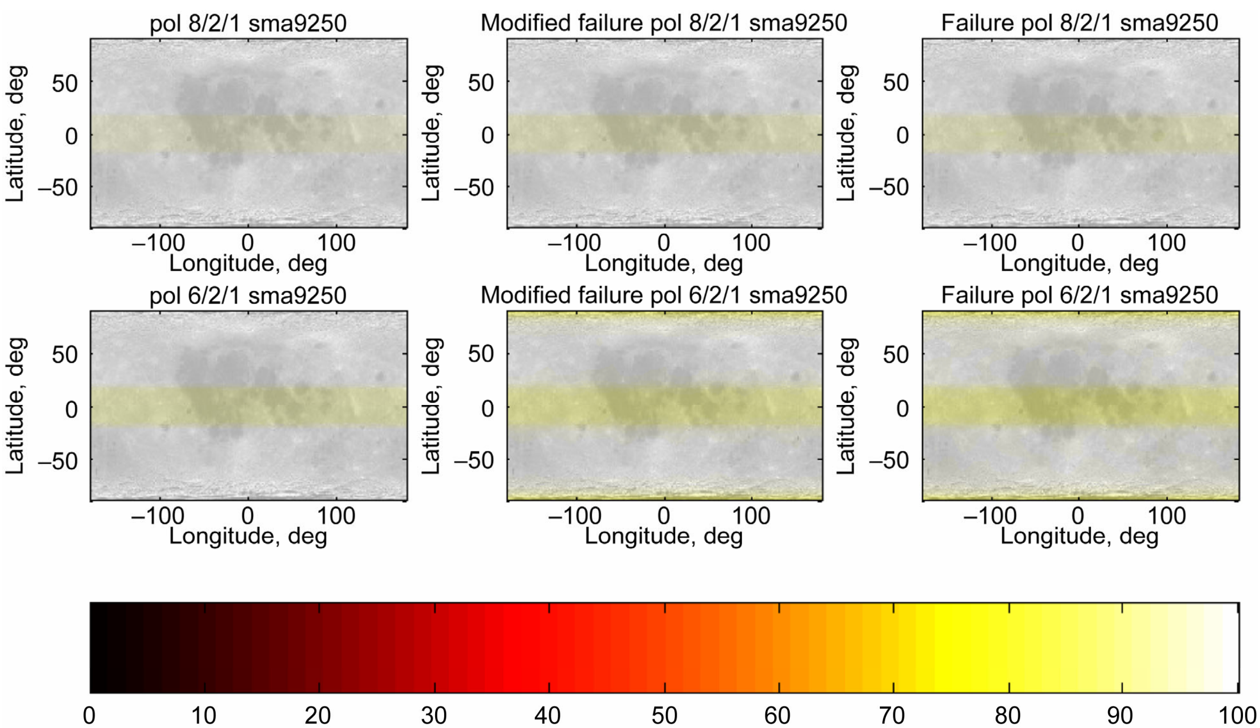

Figure D.10.1.—HDoP kinematic system availability performance for 5° elevation angle with good terrain, two-way operation.

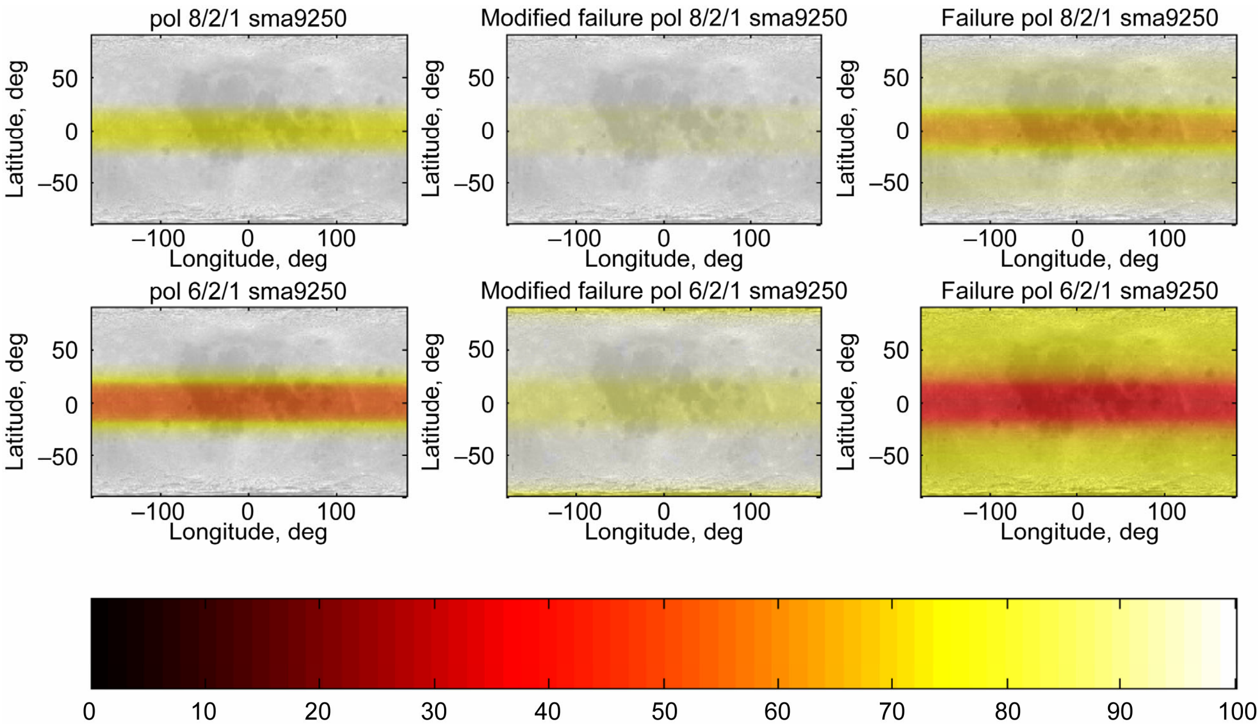

Figure D.10.2.—HDoP kinematic system availability performance for 10° elevation angle with good terrain, two-way operation.

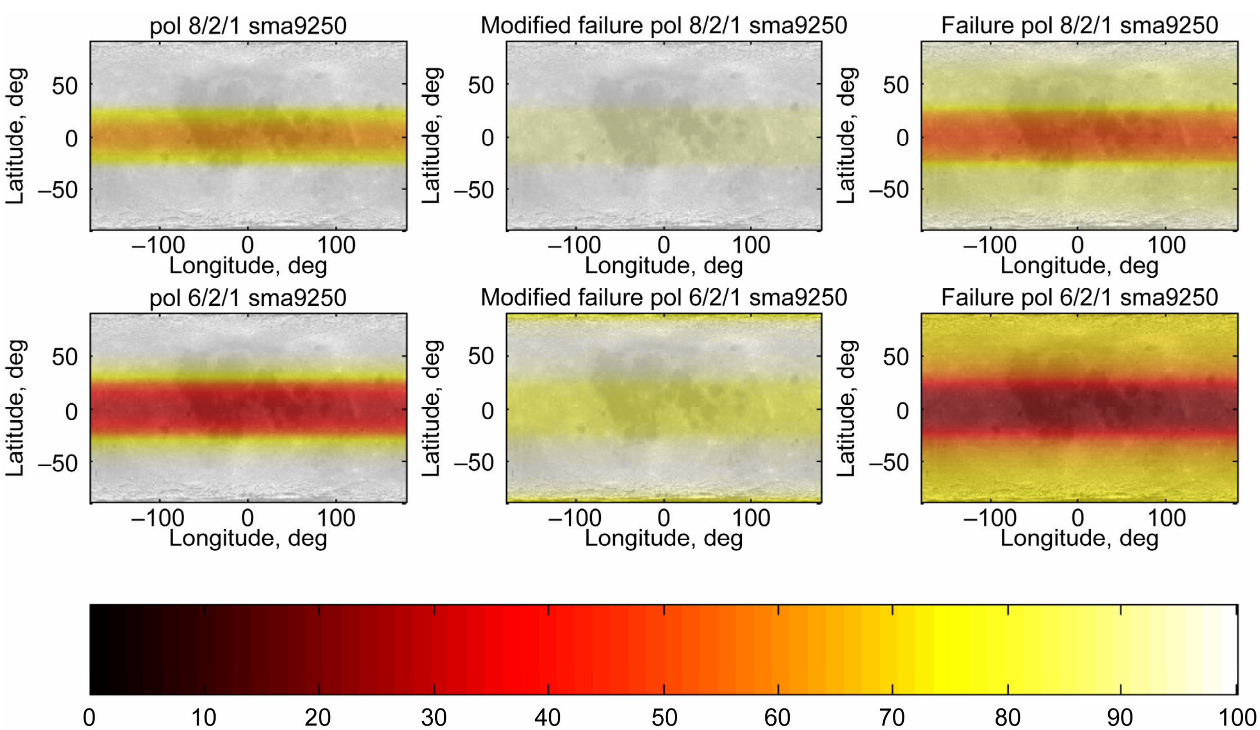

Figure D.10.3.—HDoP kinematic system availability performance for 15° elevation angle with good terrain, two-way operation.

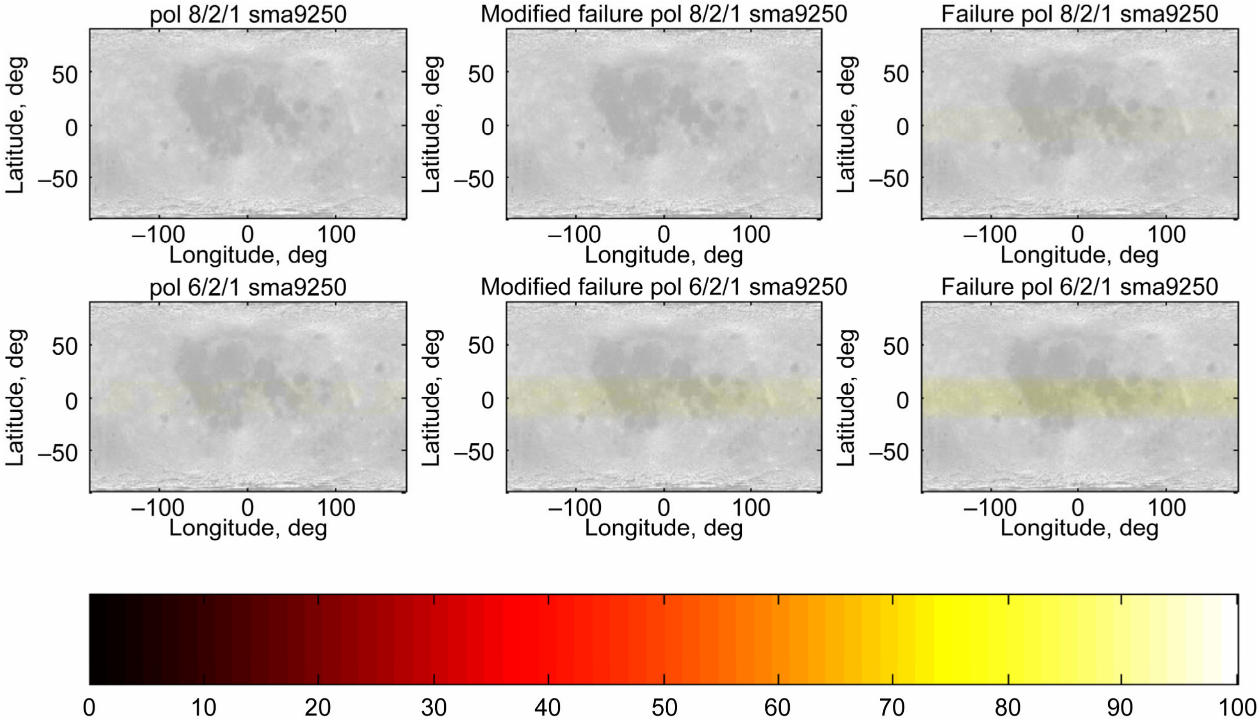

Figure D.11.1.—HDoP 15-min dynamic system availability performance for 5° elevation angle with good terrain, two-way operation.

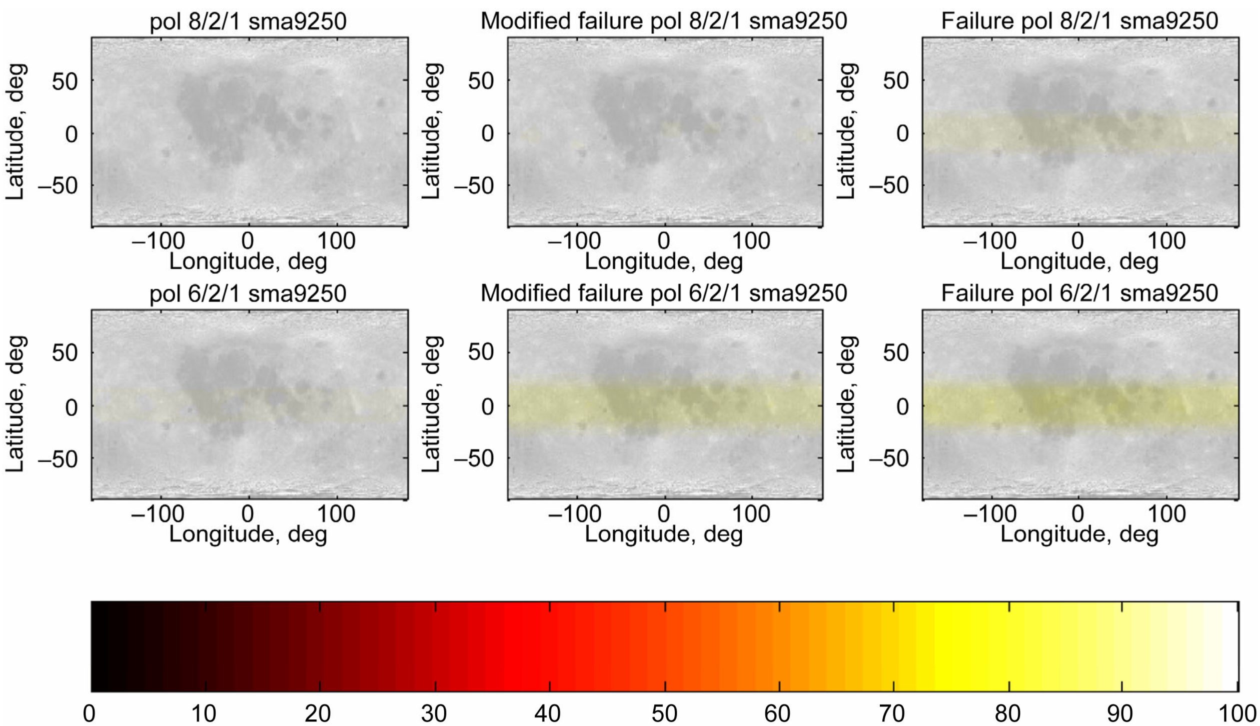

Figure D.11.2.—HDoP 15-min dynamic system availability performance for 10° elevation angle with good terrain, two-way operation.

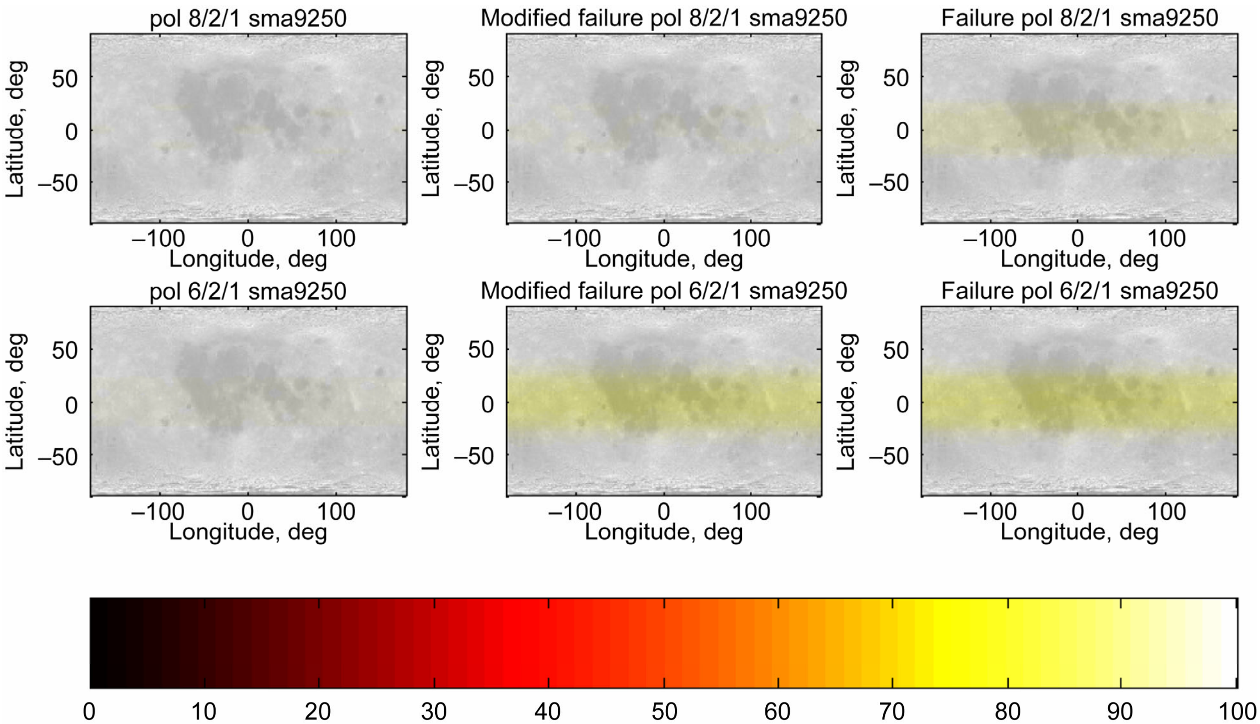

Figure D.11.3.—HDoP 15-min dynamic system availability performance for 15° elevation angle with good terrain, two-way operation.

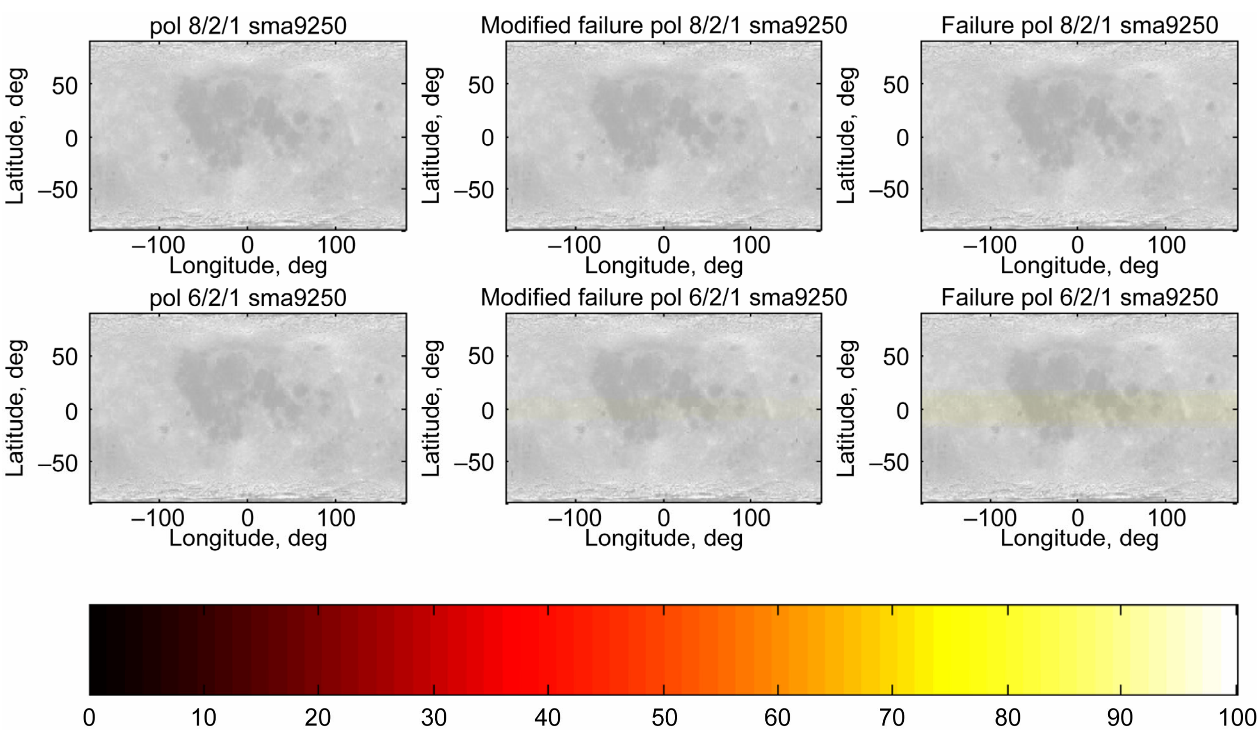

Figure D.12.1.—HDoP 1-hr dynamic system availability performance for 5° elevation angle with good terrain, two-way operation.

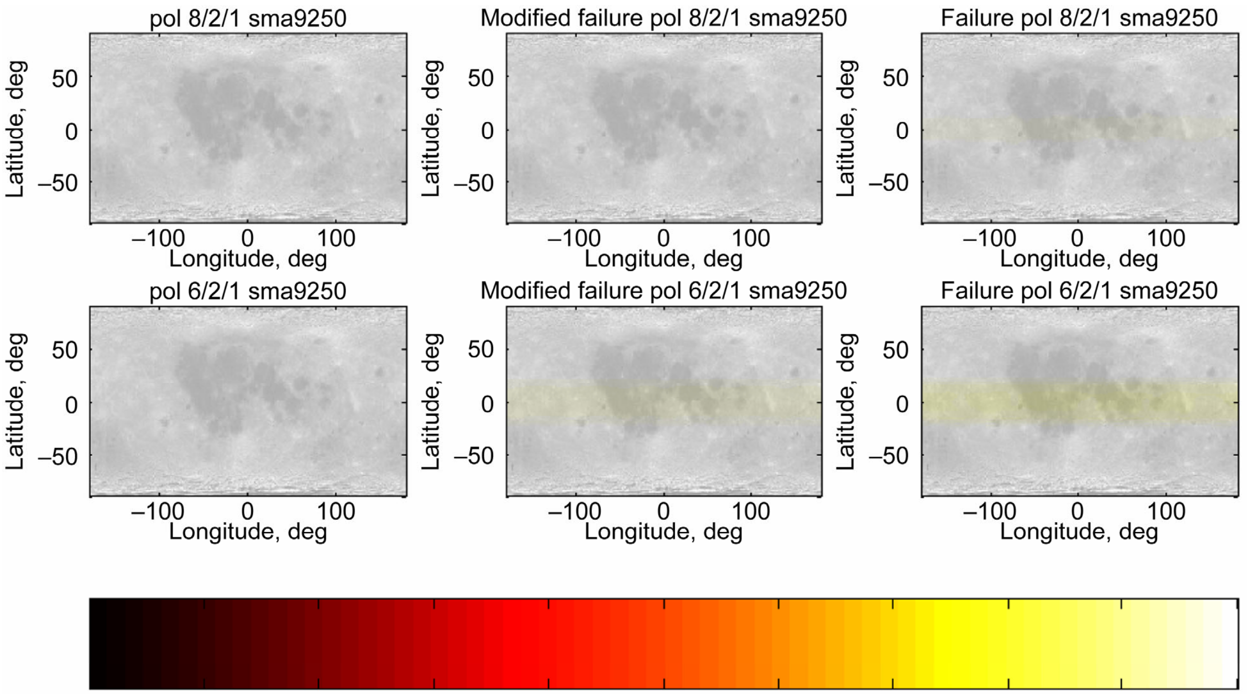

Figure D.12.2.—HDoP 1-hr dynamic system availability performance for 10° elevation angle with good terrain, two-way operation.

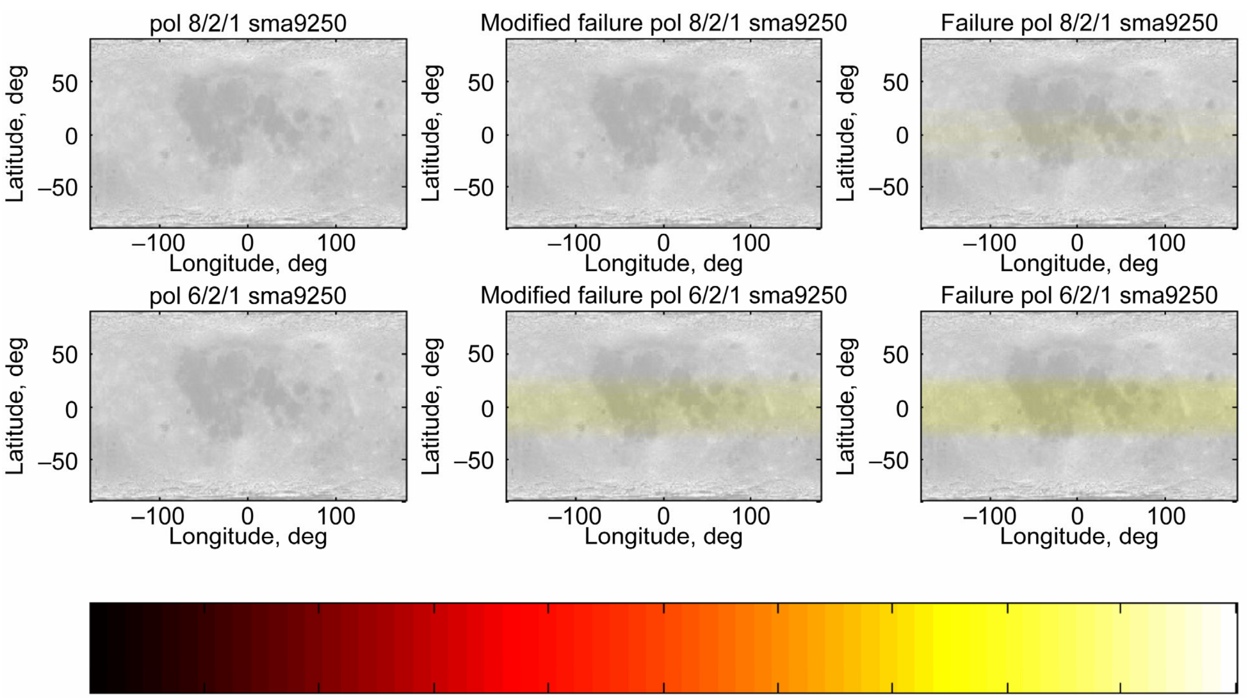

Figure D.12.3.—HDoP 1-hr dynamic system availability performance for 15° elevation angle with good terrain, two-way operation.

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14. ABSTRACT With the NASA Vision for Space Exploration focusing on the return of astronauts to the Moon and eventually to Mars, architectures for new navigation concepts must be derived and analyzed. One such concept, developed by the Space Communications Architecture Working Group (SCAWG), is to place a constellation of satellites around the Moon. Previously completed analyses examined the performance of multiple satellite constellations and recommended a constellation oriented as a Walker polar 6/2/1 with a semimajor axis (SMA) of 9250 km. One requirement of the constellations that were examined was that they have continuous access to any location on the lunar surface. In this report, the polar 6/2/1 and polar 8/2/1, with equal SMAs, are examined in greater detail. The dilution-of-precision (DoP) methodology is utilized to examine the effects of longitude surface points, latitude surface points, elevation requirements, and modified failure modes for these two constellations with regard to system availability. Longitude study results show that points along a meridian closely approximate the results of a global set of data points. Latitude study results show that previous assumptions with regard to latitude spacing are adequate to simulate global system availability. Elevation study results show that global system availability curves follow a reverse sigmoid function. Modified failure mode study results show that the benefits of reorienting a failure mode constellation depend on the type of navigation system and the length of the integration period being used.						
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